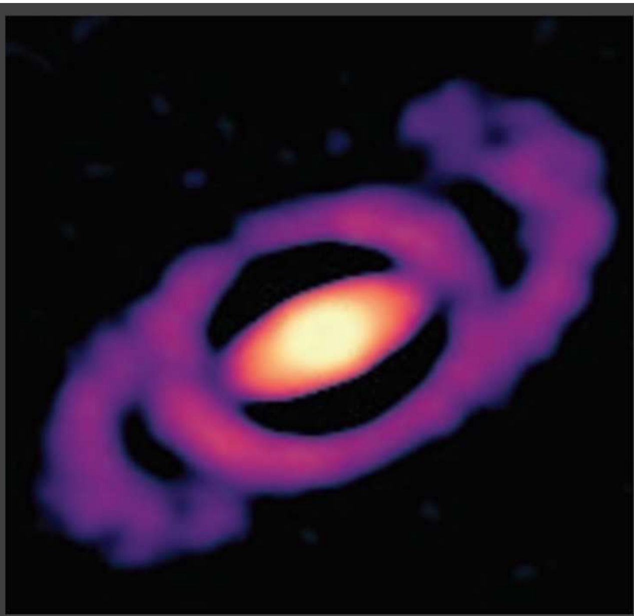
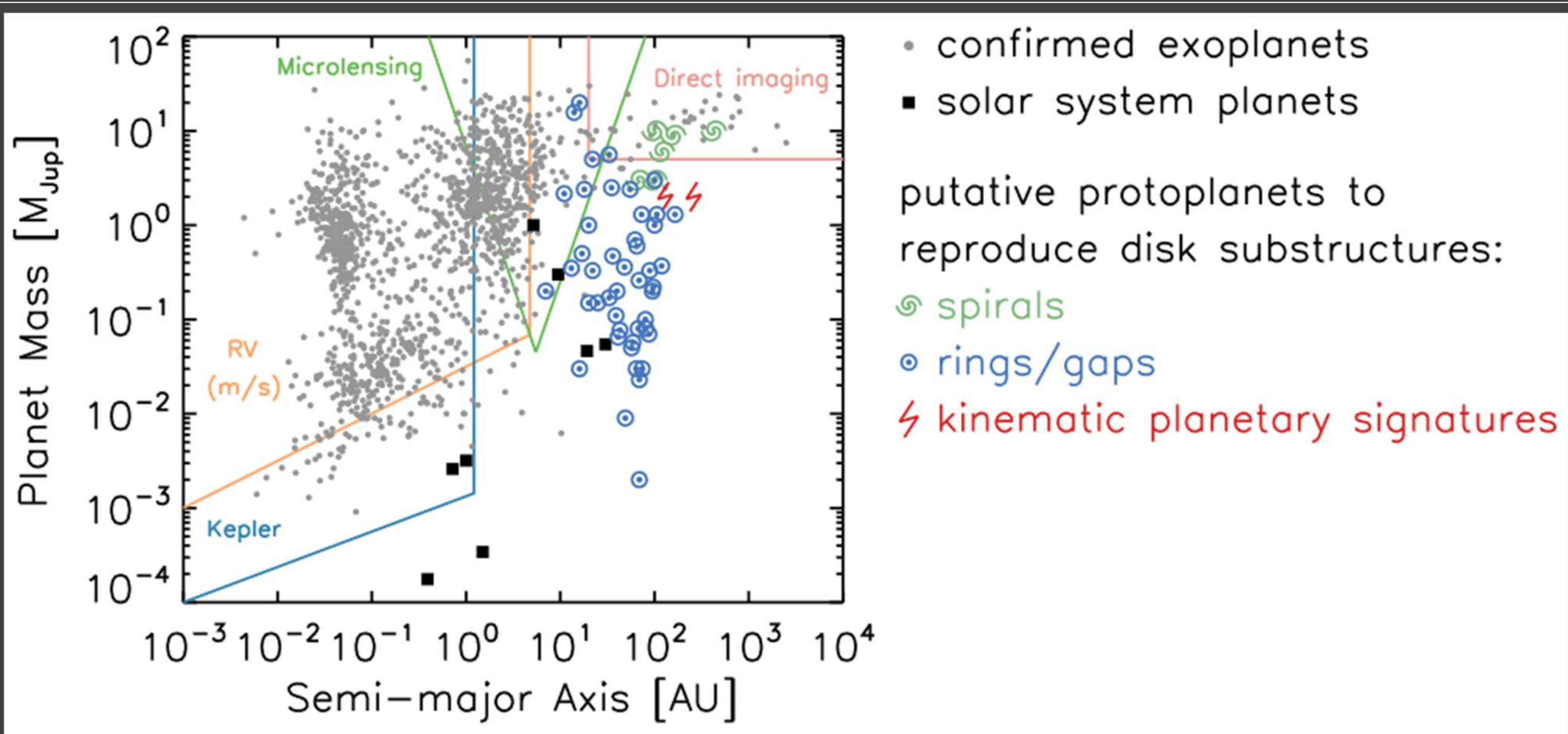


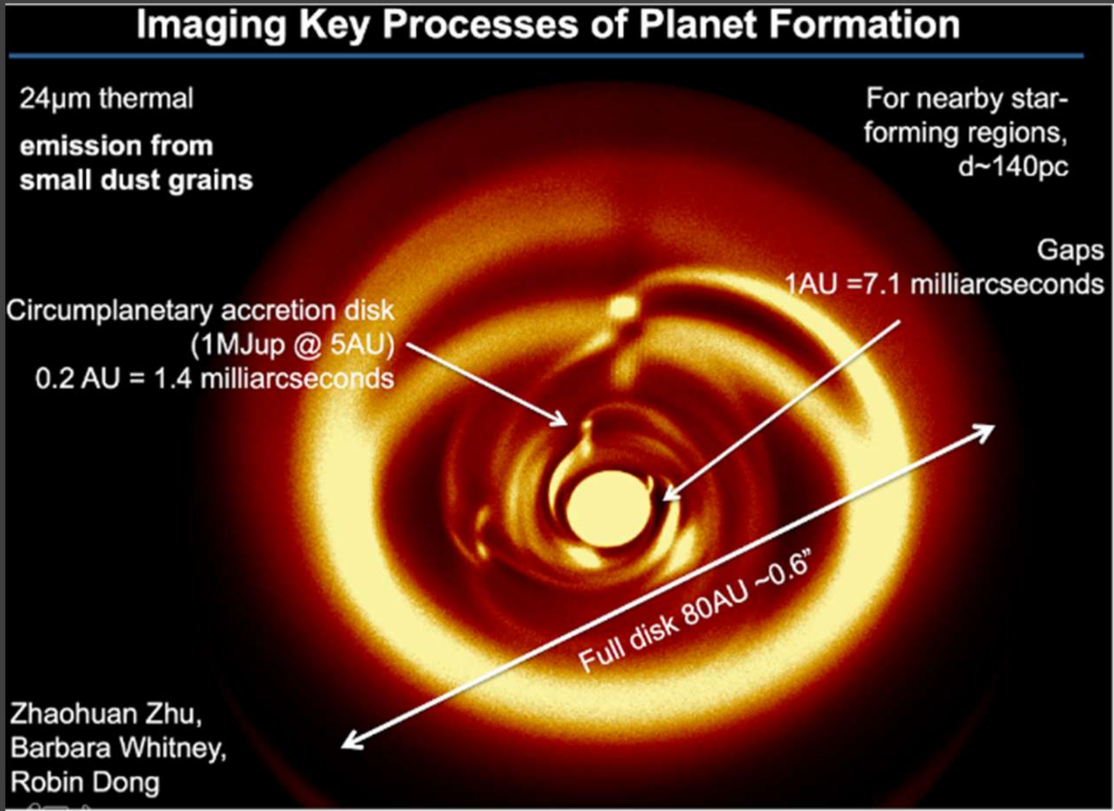
Young planetary systems

SERGEI POPOV

Planets and discs



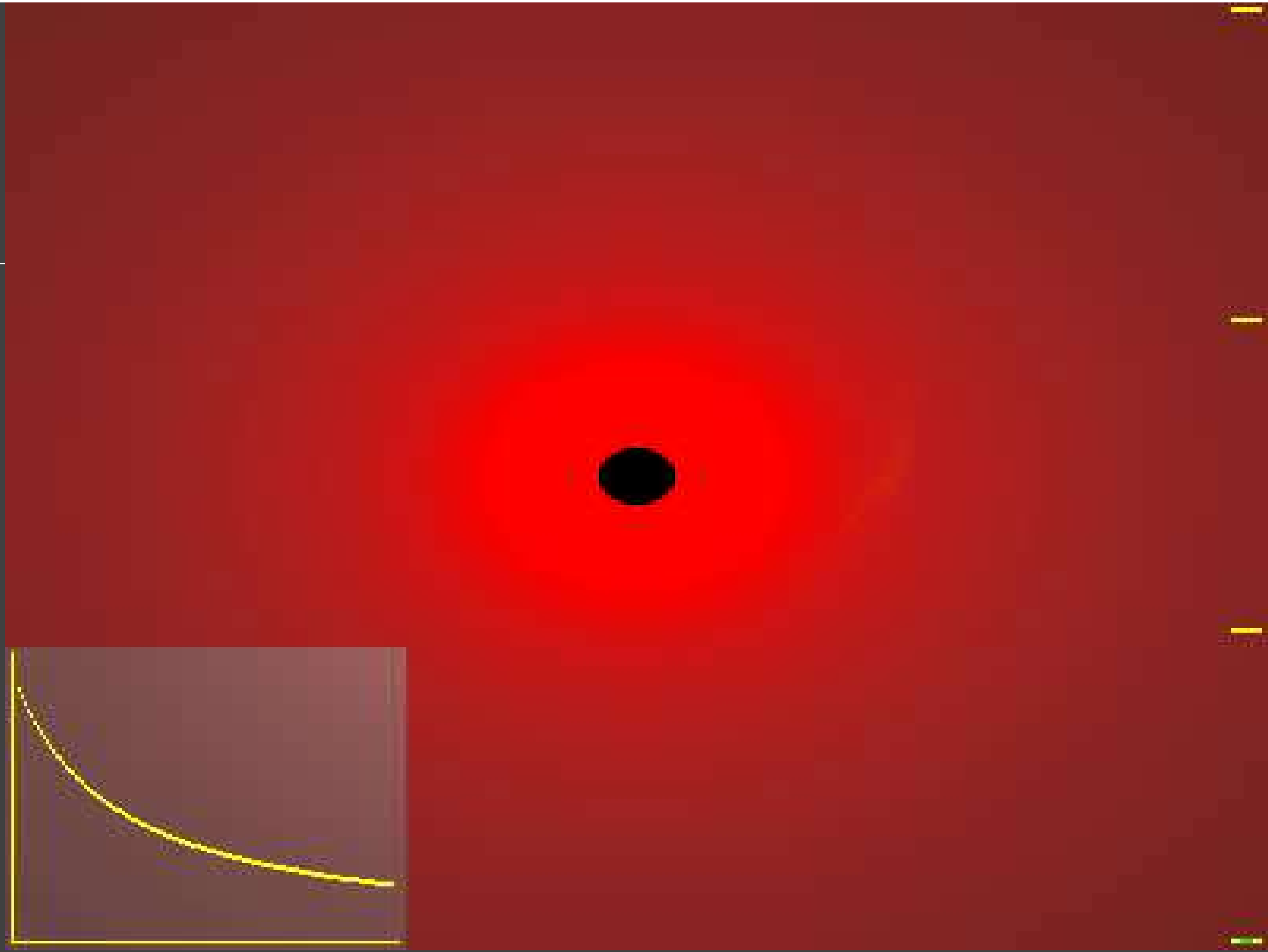
Modeling and imaging planet formation



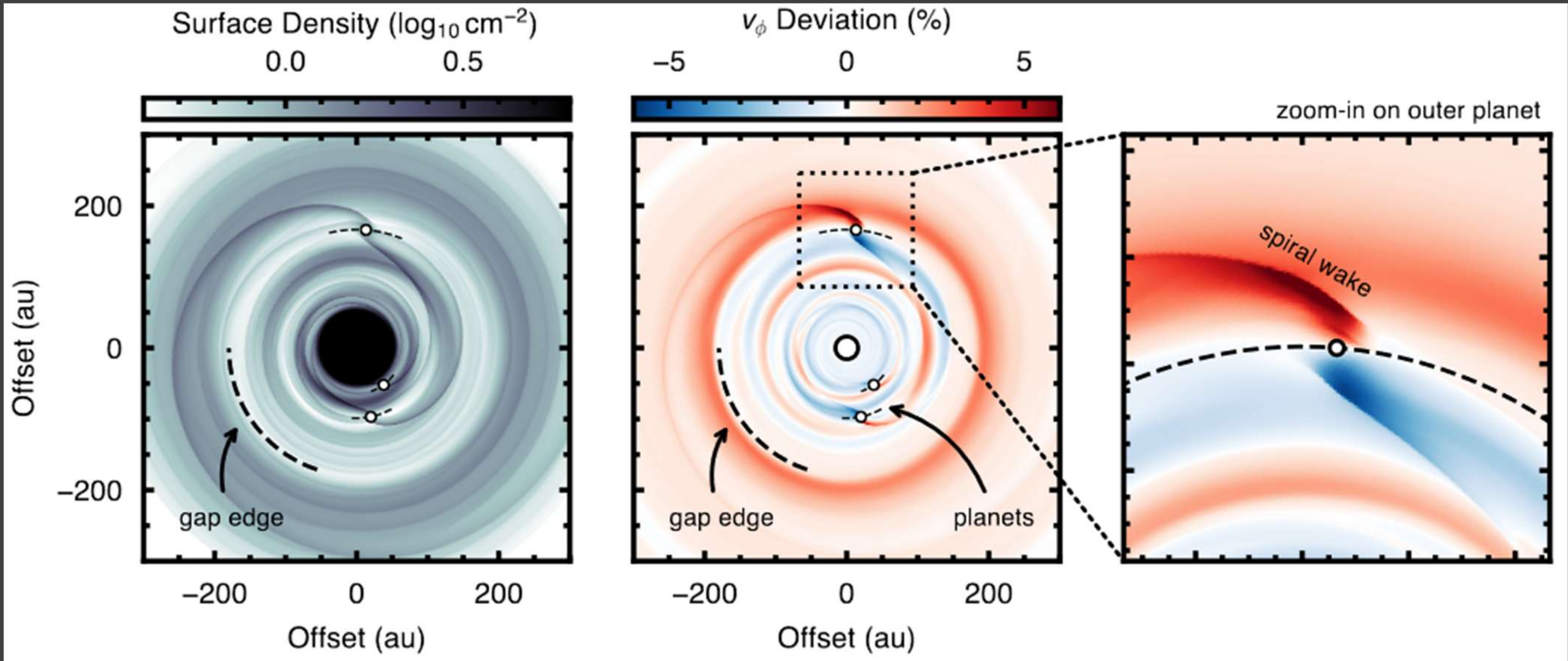
Feature	Scale	Methods
Overall Disk	80au	mm-wave (ALMA); Coronagraphy on 8+meter telescopes; JWST
Large gaps and structures	5-20au	mm-wave (ALMA); Radio (ngVLA); Coronagraphy on 8+meter telescopes; JWST
Terrestrial Planet Zone	<4au	30m telescope; IR interferometry (CHARA,VLTI, MROI)
Gaps and accretion streams from individual planets	<1au	mm-wave (ALMA); 30m telescopes; IR interferometry (CHARA, VLT, MROI)
Circum*planetary* Disks	<0.2au	IR interferometry (FUTURE FACILITY)

1907.09564

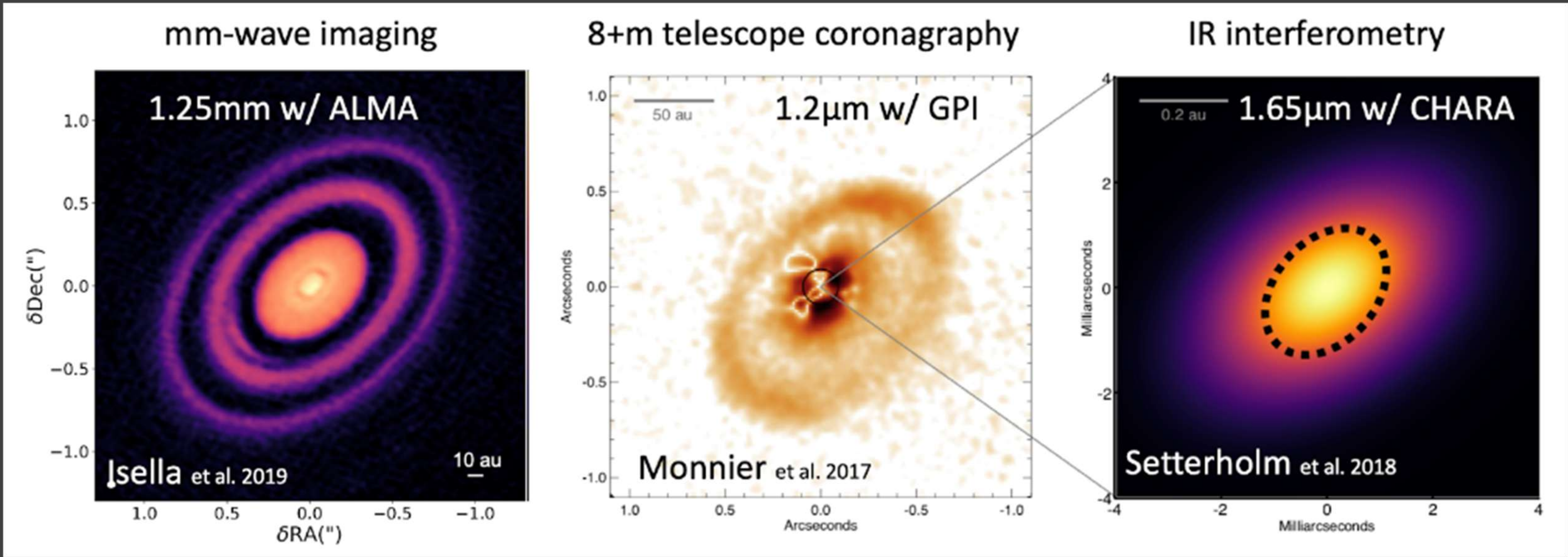
Picture shows results of computer simulation.



Planet-disc interaction

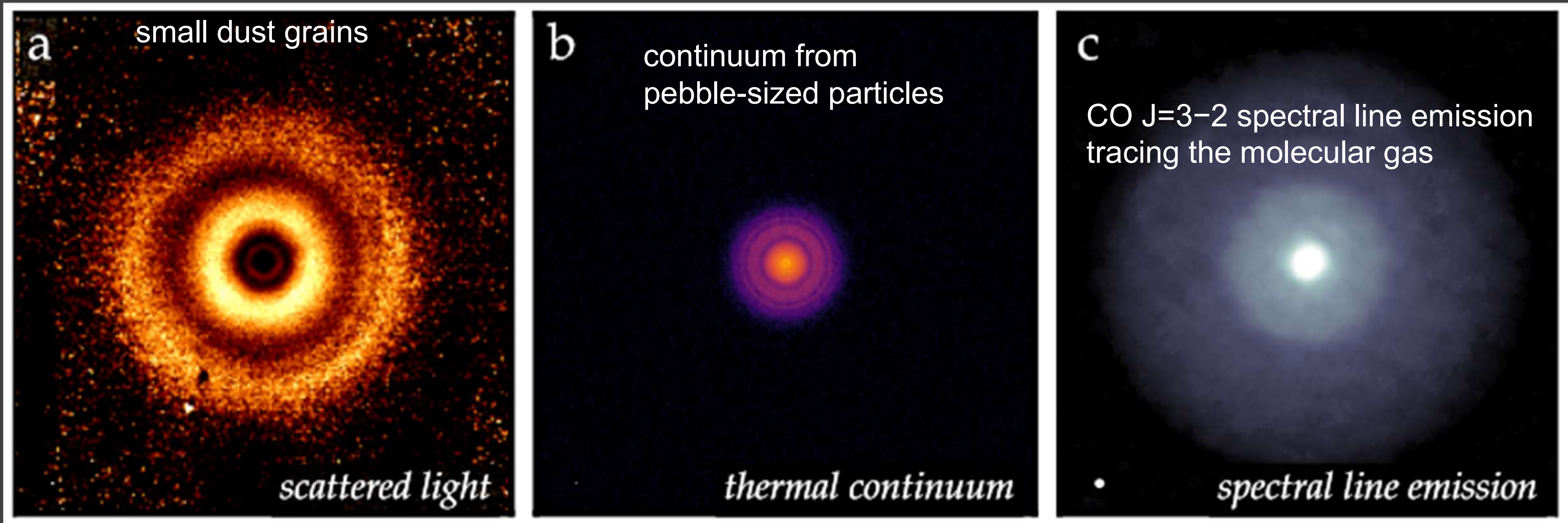


More details with different techniques

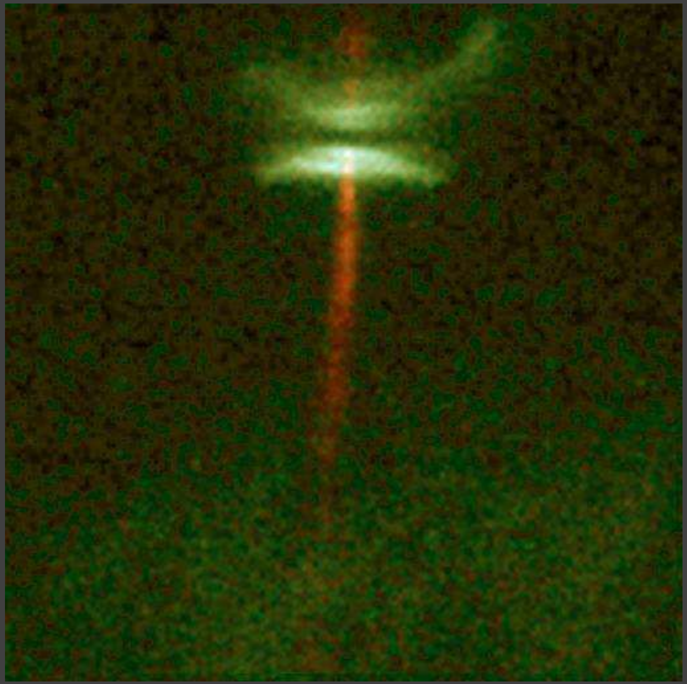


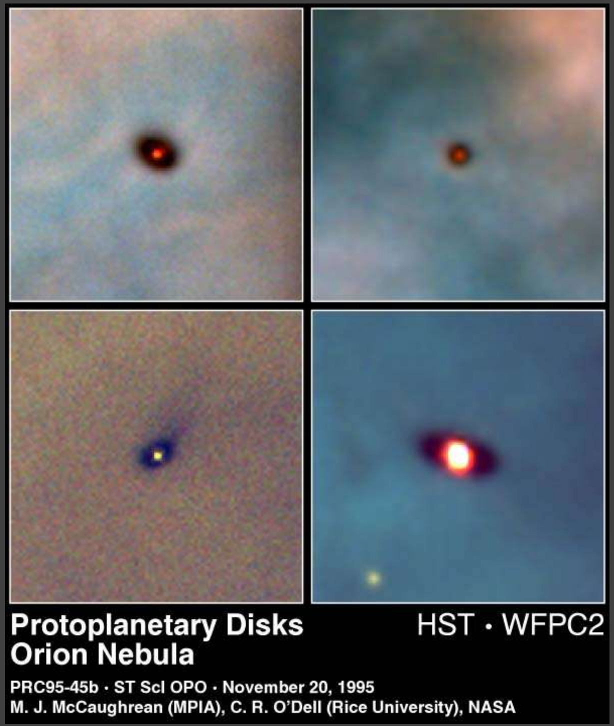
Different structures in different light

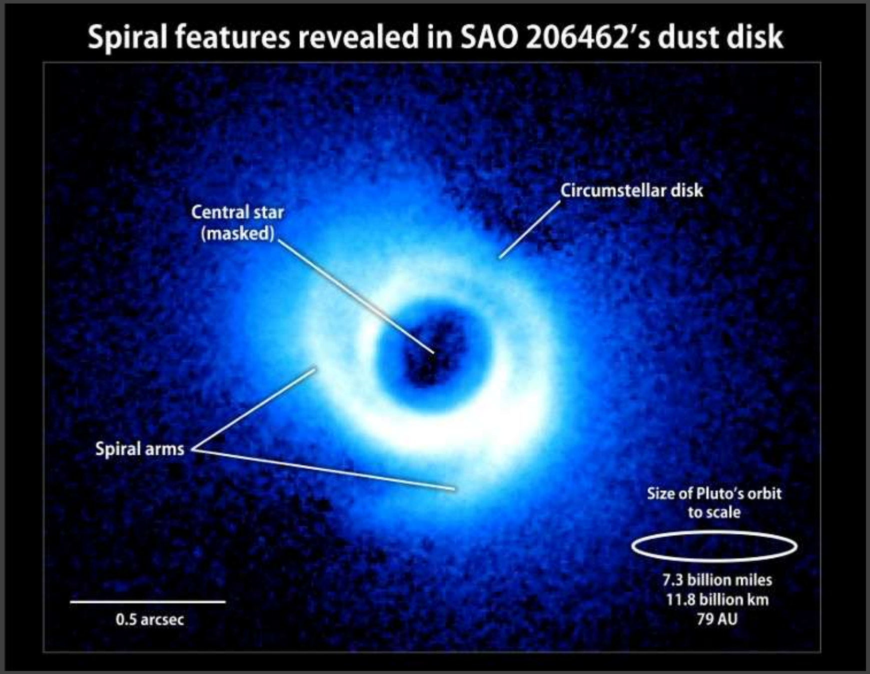
TW Hya disk



Protoplanetary discs







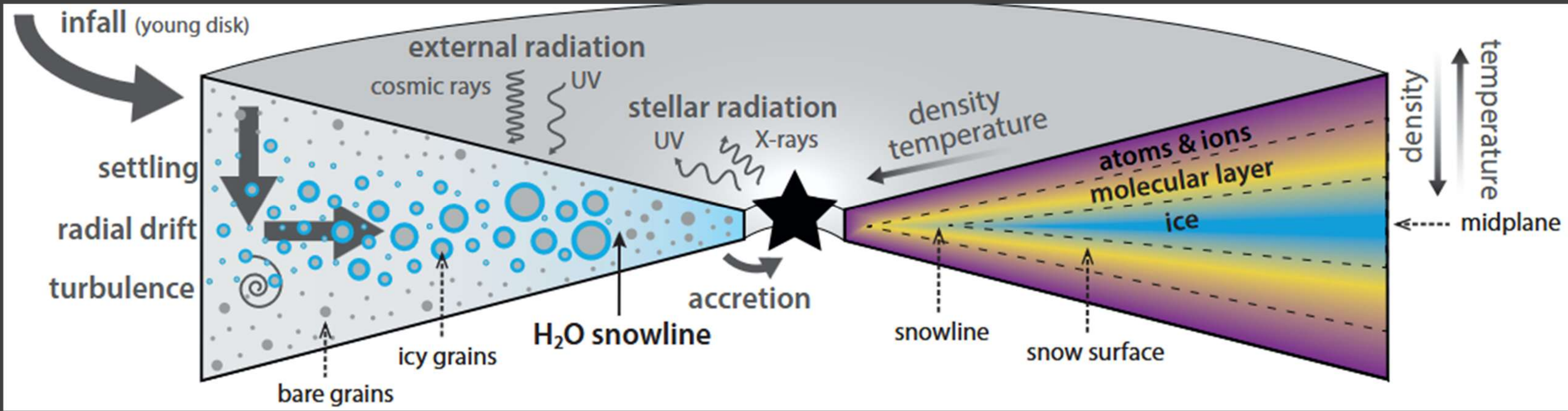
https://online.science.psu.edu/astro140_sp201314wd001/node/7717
http://news.softpedia.com/news/Exoplanets-Can-Form-Spiral-in-Stellar-Protoplanetary-Disks-228792.shtml

Dusty discs


HST observations

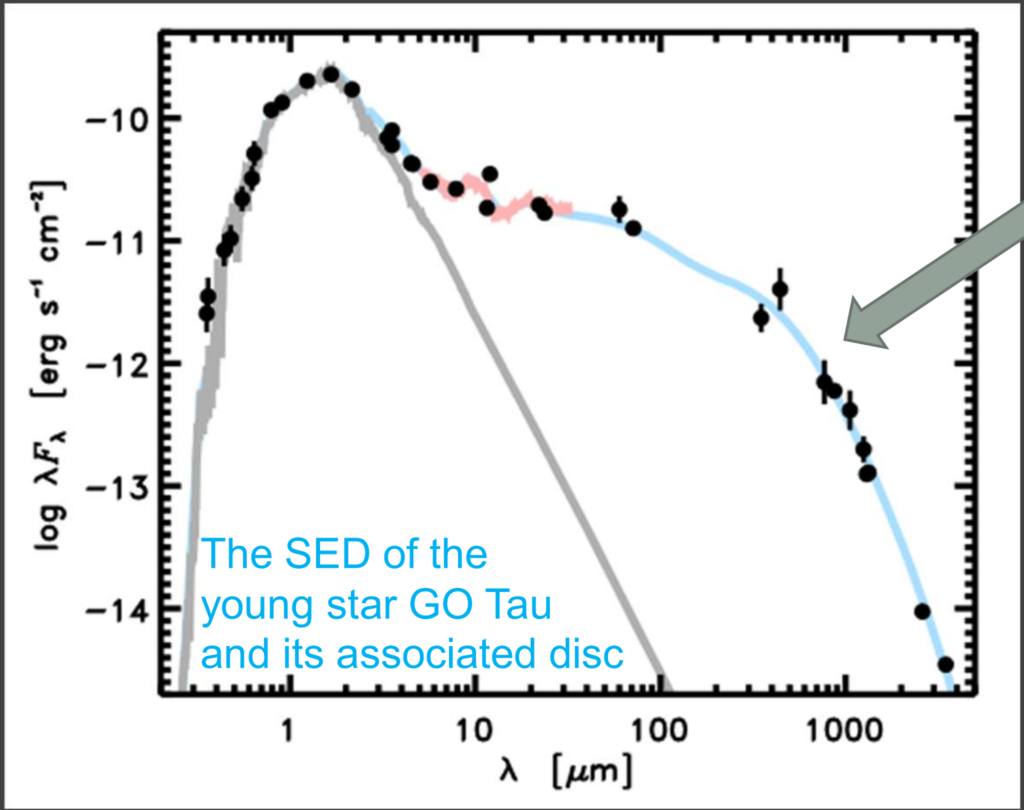
Disc is visible edge-on.

Disc structure



2410.23235

Discs and stars



Optically thin disc.
Allows to determine dust mass.

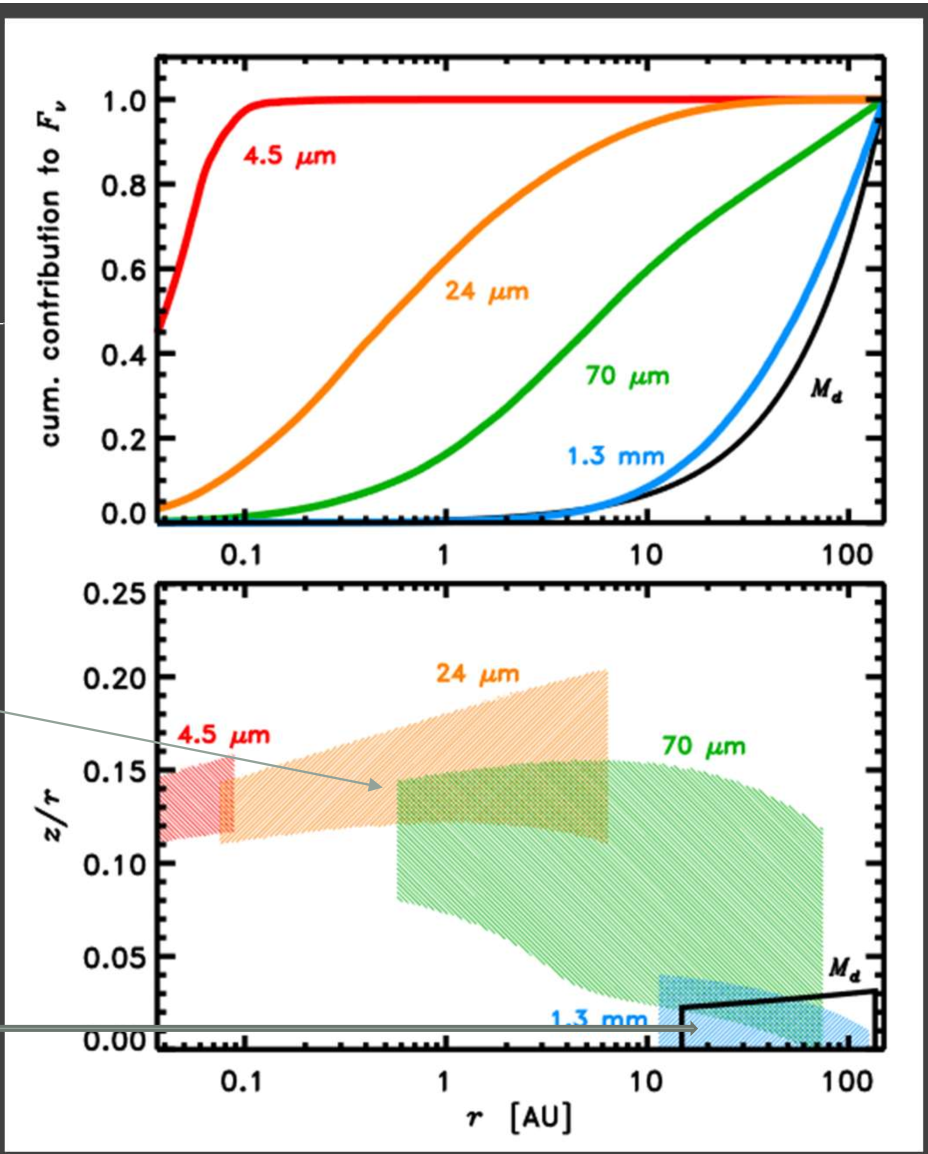
$$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})},$$

See 1807.09631
about different methods
of dust mass determination

$$M_{\rm dust} \propto M_{\rm star}^{1.8}.$$

Dust in the disc

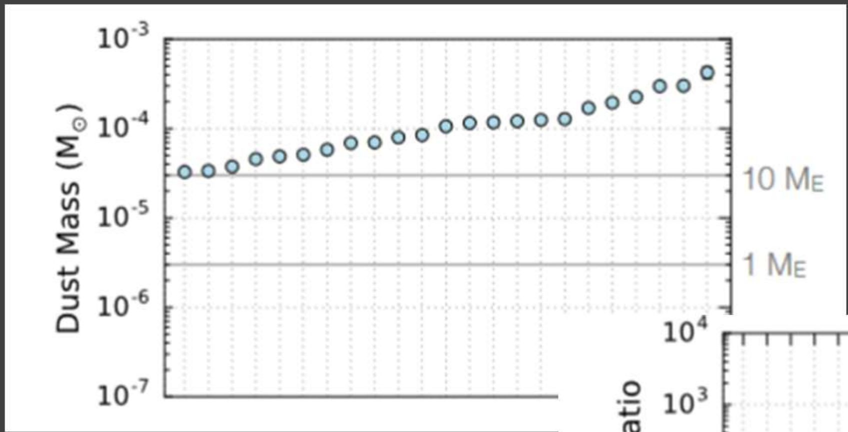
Observations in different wavelengths allow to probe different parts of the disc and determine dust mass and distribution.

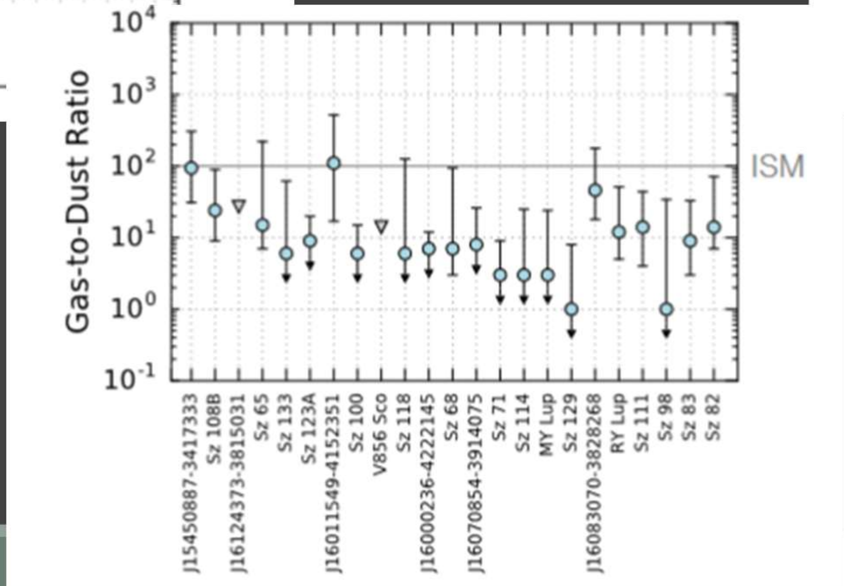


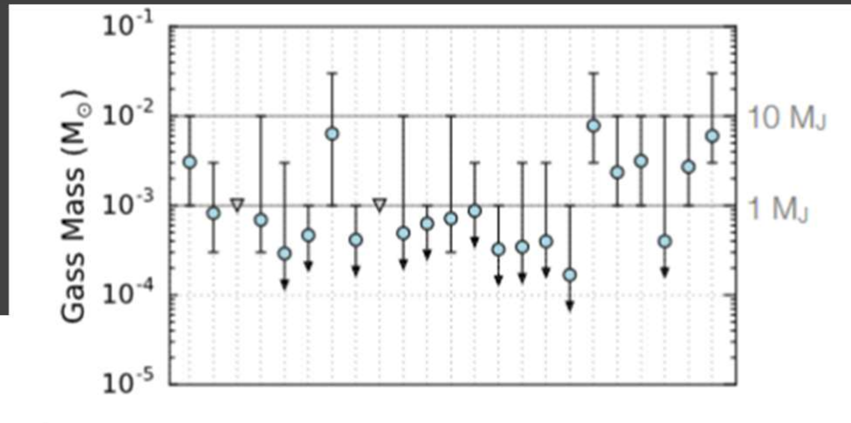
Regions of 80% of emission in each band

80% of dust

Disc mass: gas + dust



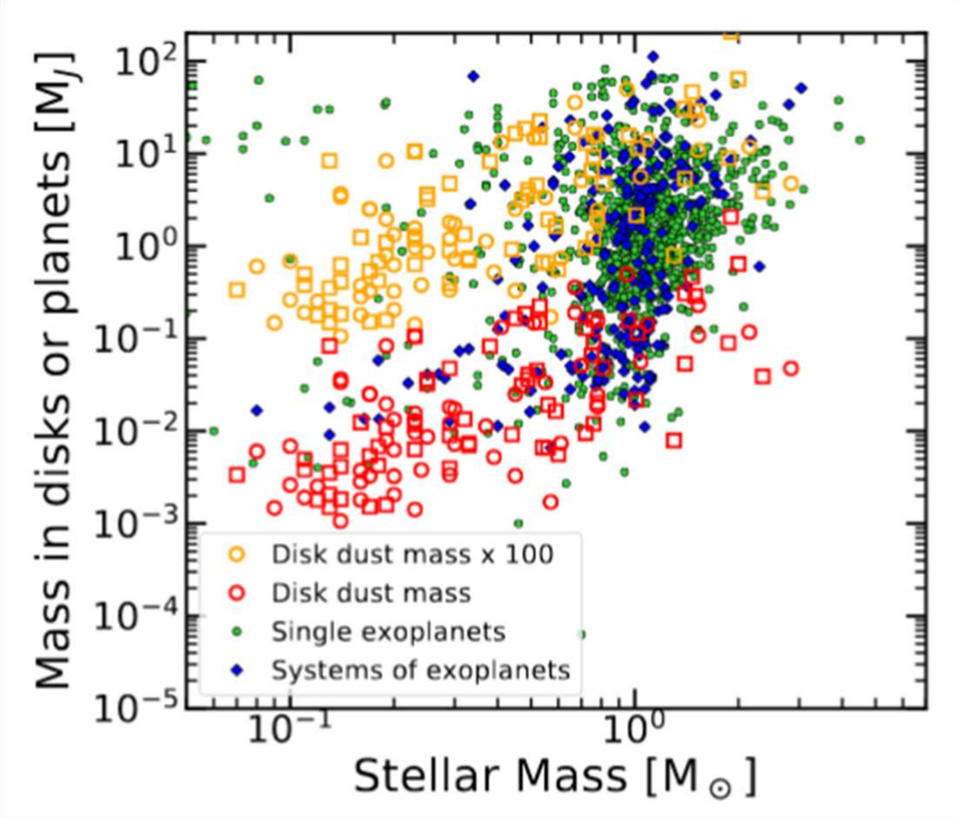


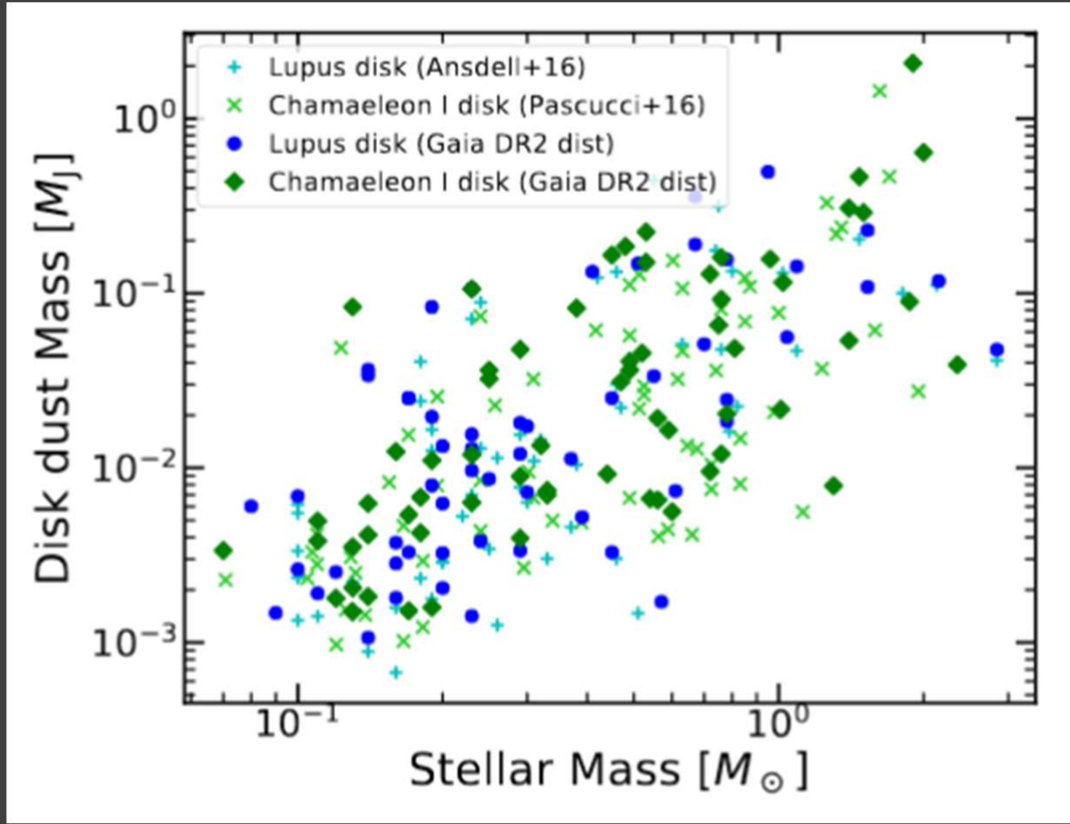


Gas mass determined
by CO observations (ALMA).

1807.09631

Disc mass vs. star mass

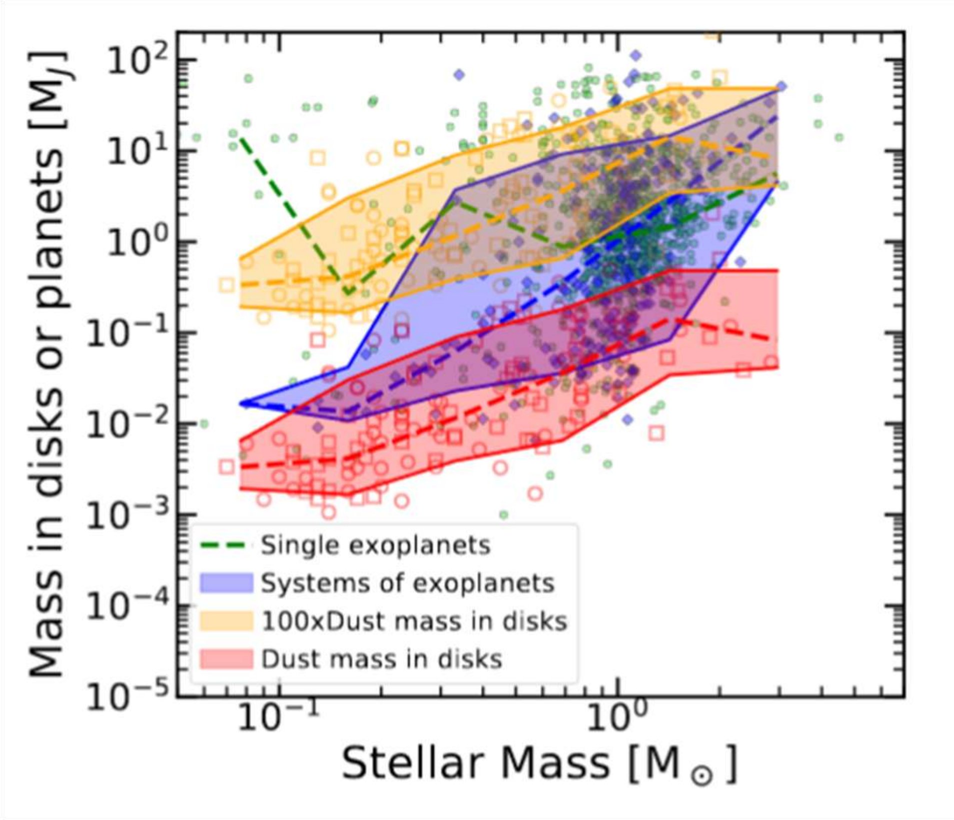


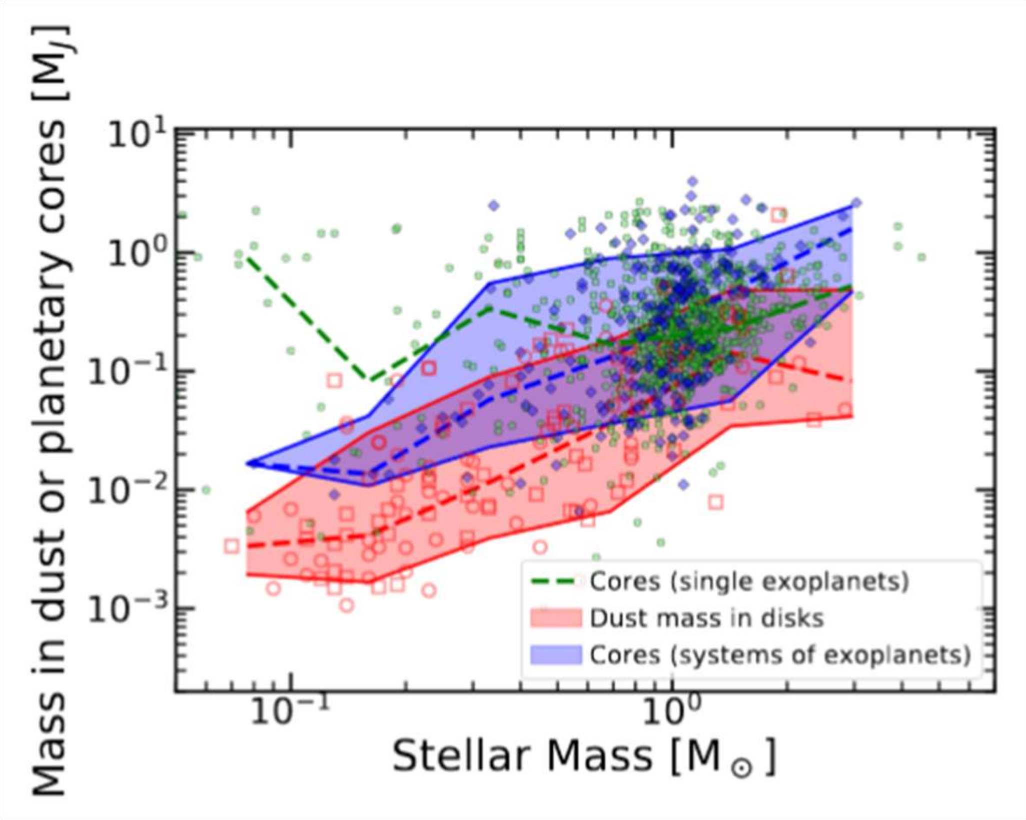


1809.07374

Not enough mass is discs??? Rapid early evolution??? See also 2605.26216

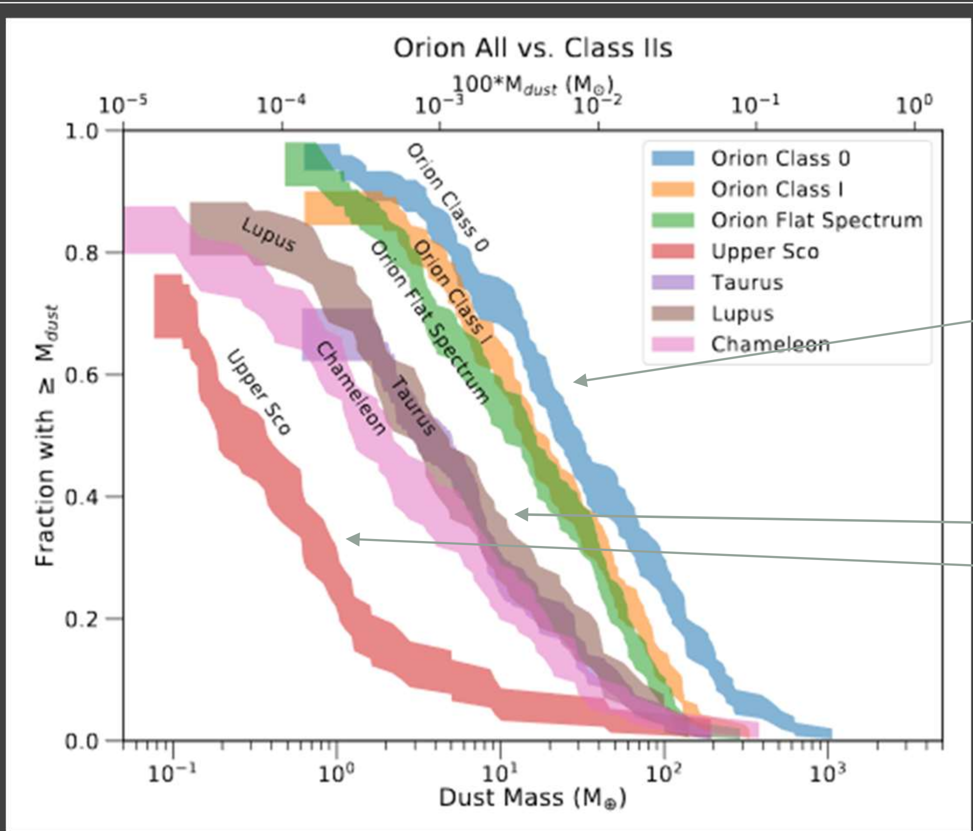
Disc and planet mass correlations with the stellar mass





1809.07374

Indeed, evolution, baby

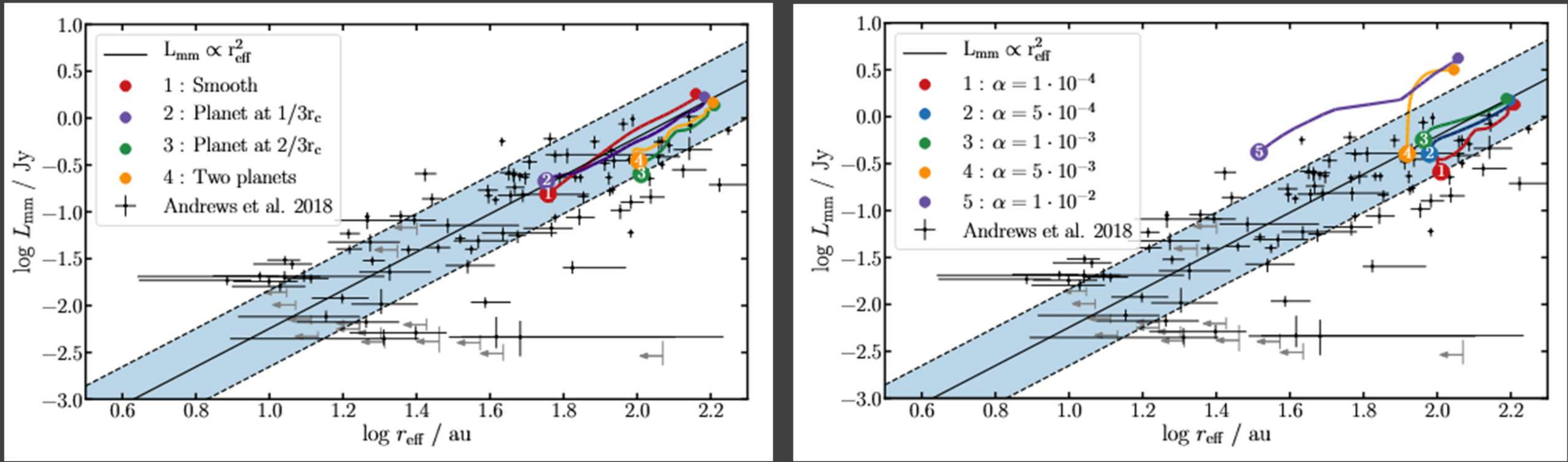


328 protostars
ALMA and VLA observations

Young discs

Older discs

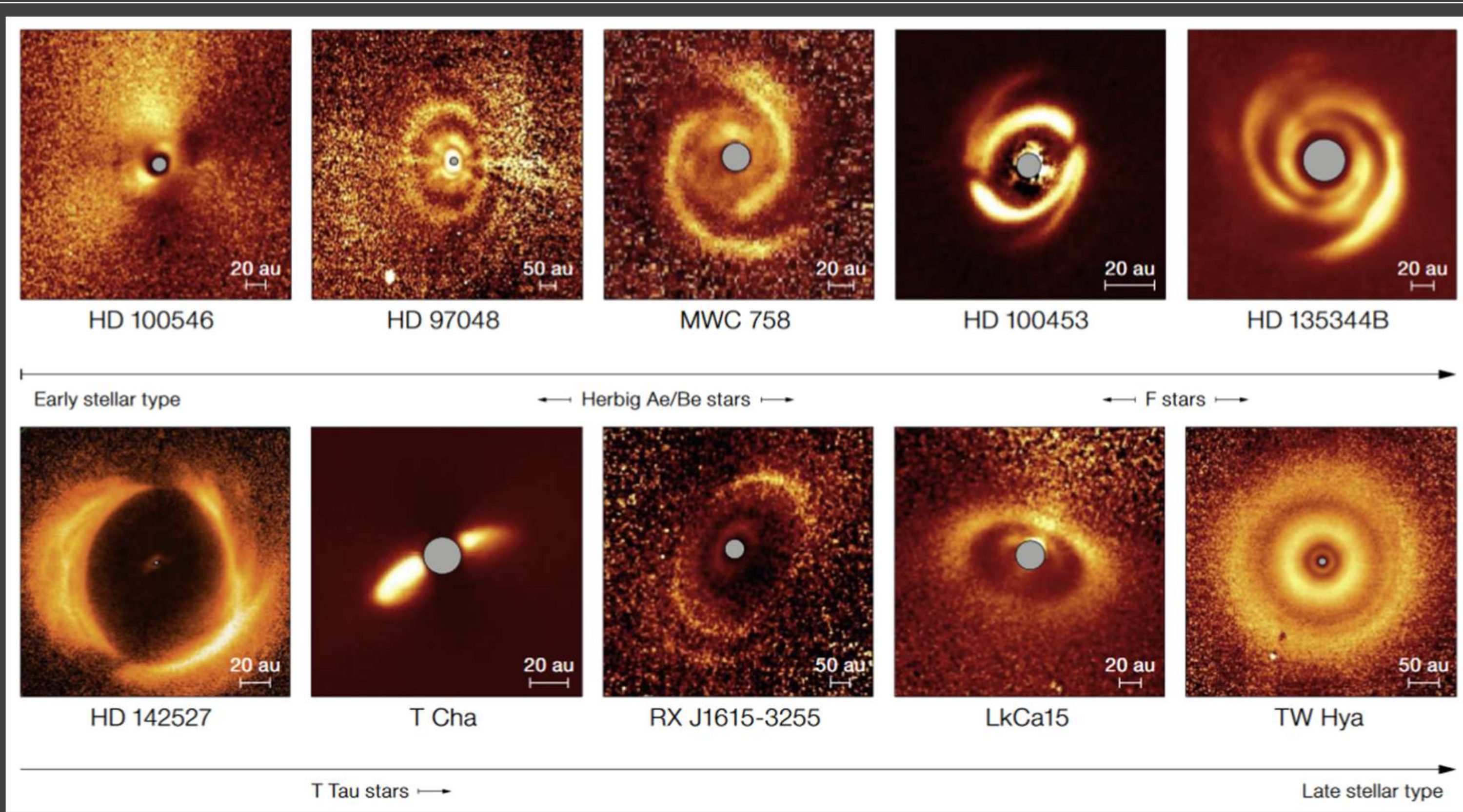
Population modeling of protoplanetary discs



Discs with and without massive planets have different relations Luminosity vs. size.

2202.01241

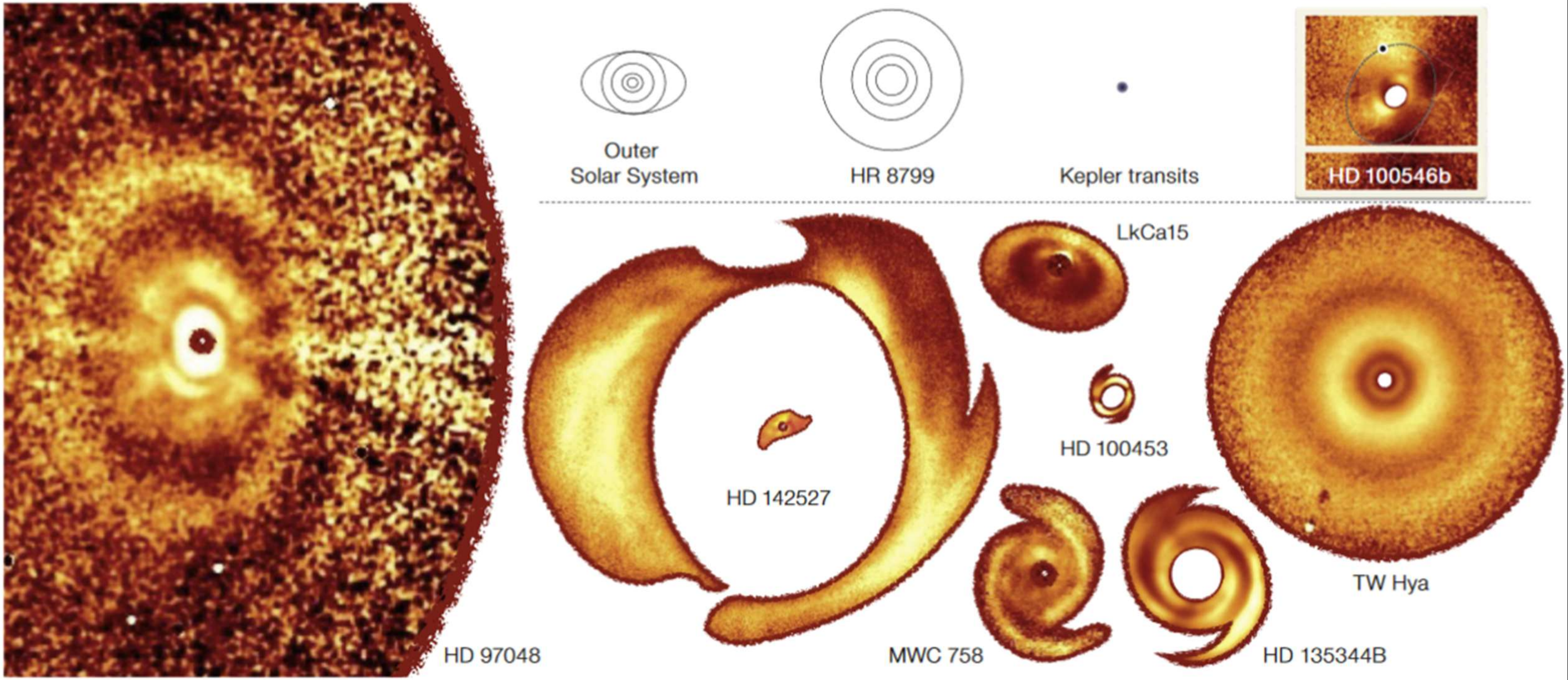
VLT/SPHERE



0.5-2.3 micrometers

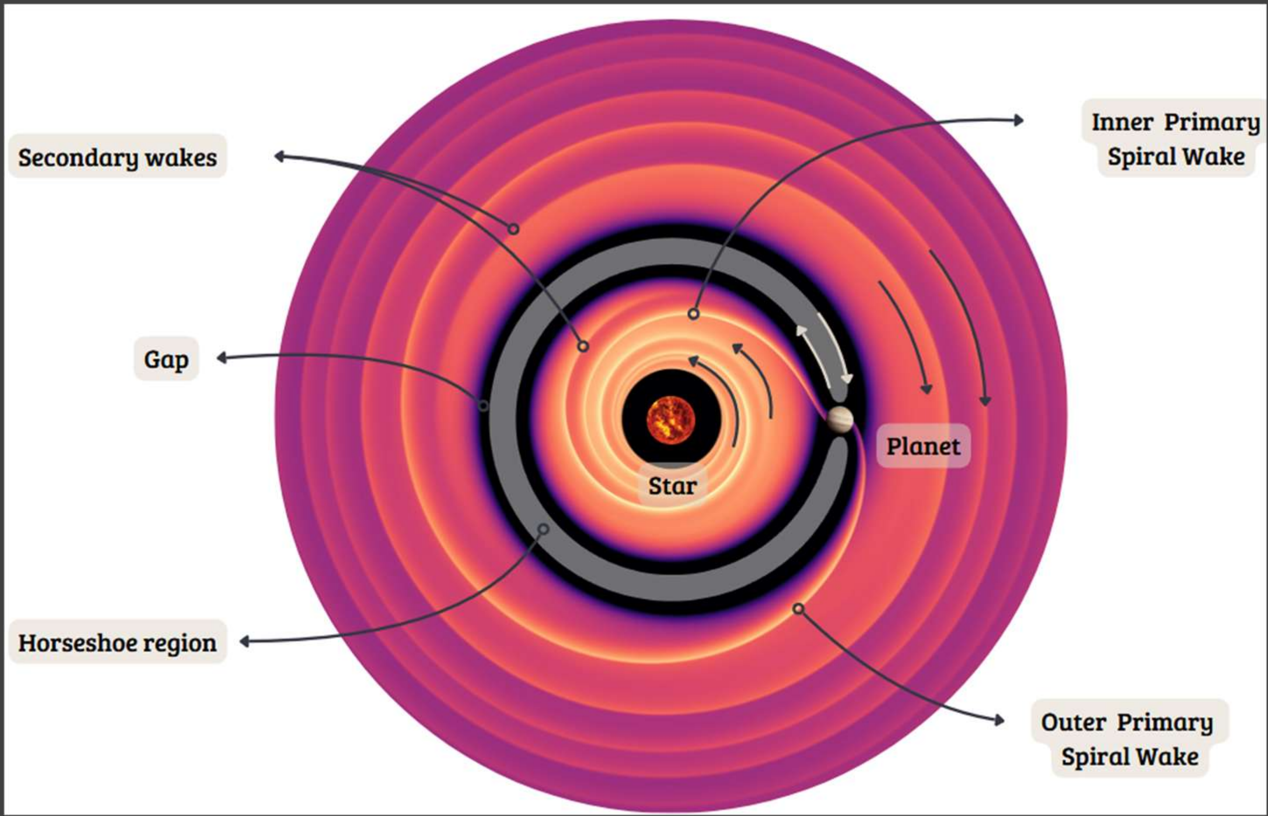
1710.02795

PDI images are sensitive to micron-sized dust grains at the disc surface

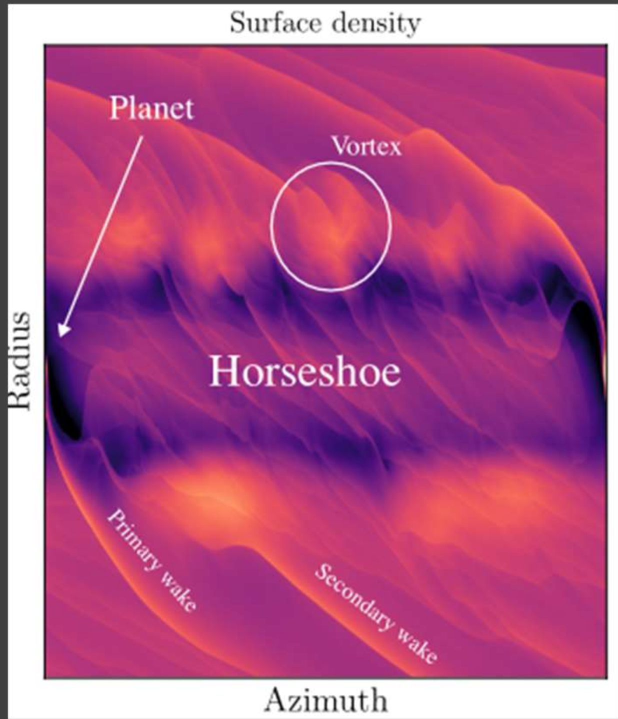

Outer
Solar System
HR 8799
Kepler transits
HD 100546b
LkCa15
HD 142527
HD 100453
TW Hya
HD 97048
MWC 758
HD 135344B

1710.02795

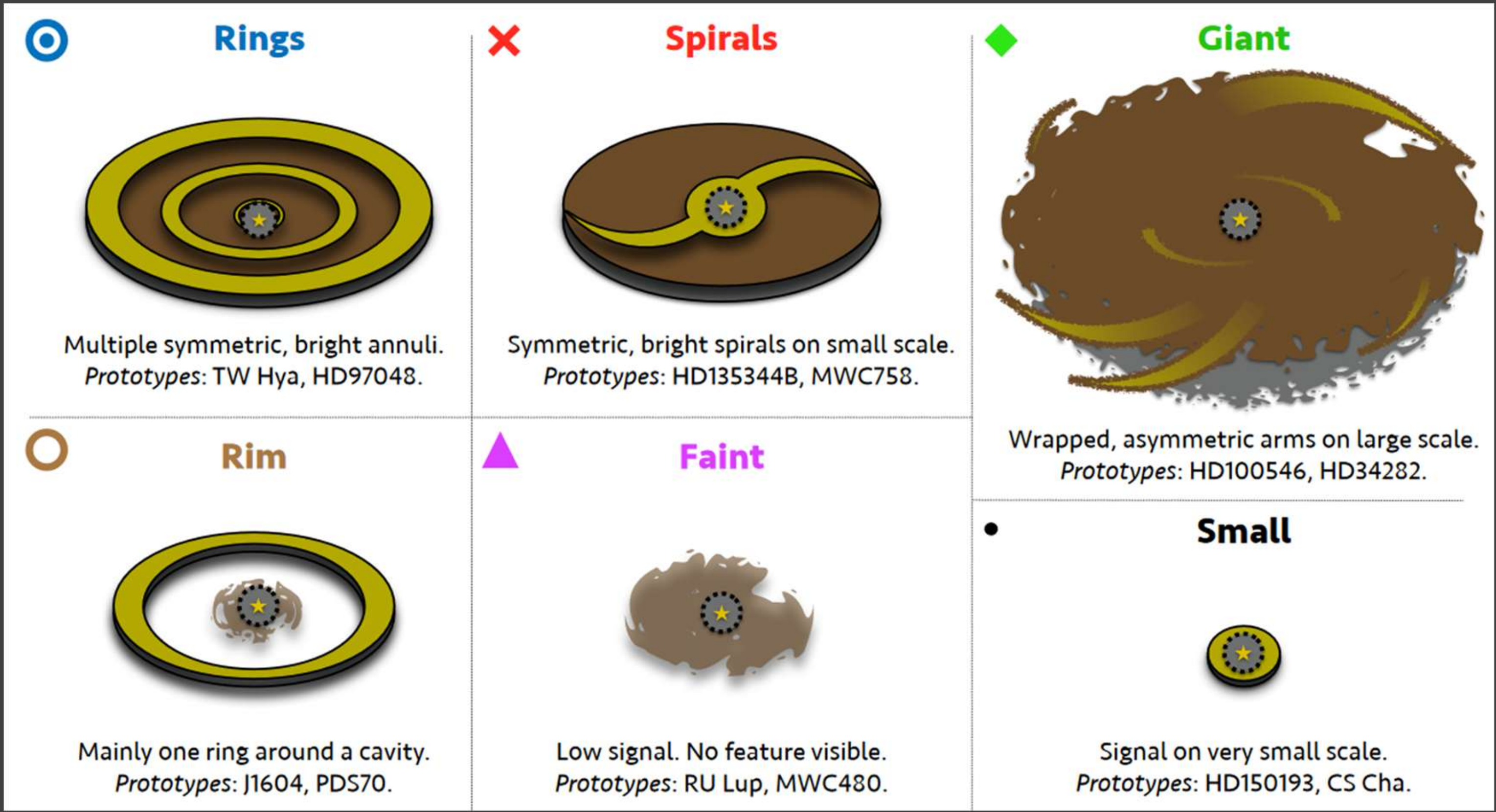
Planet-disk interaction



Structures in disks are mainly formed by planets.

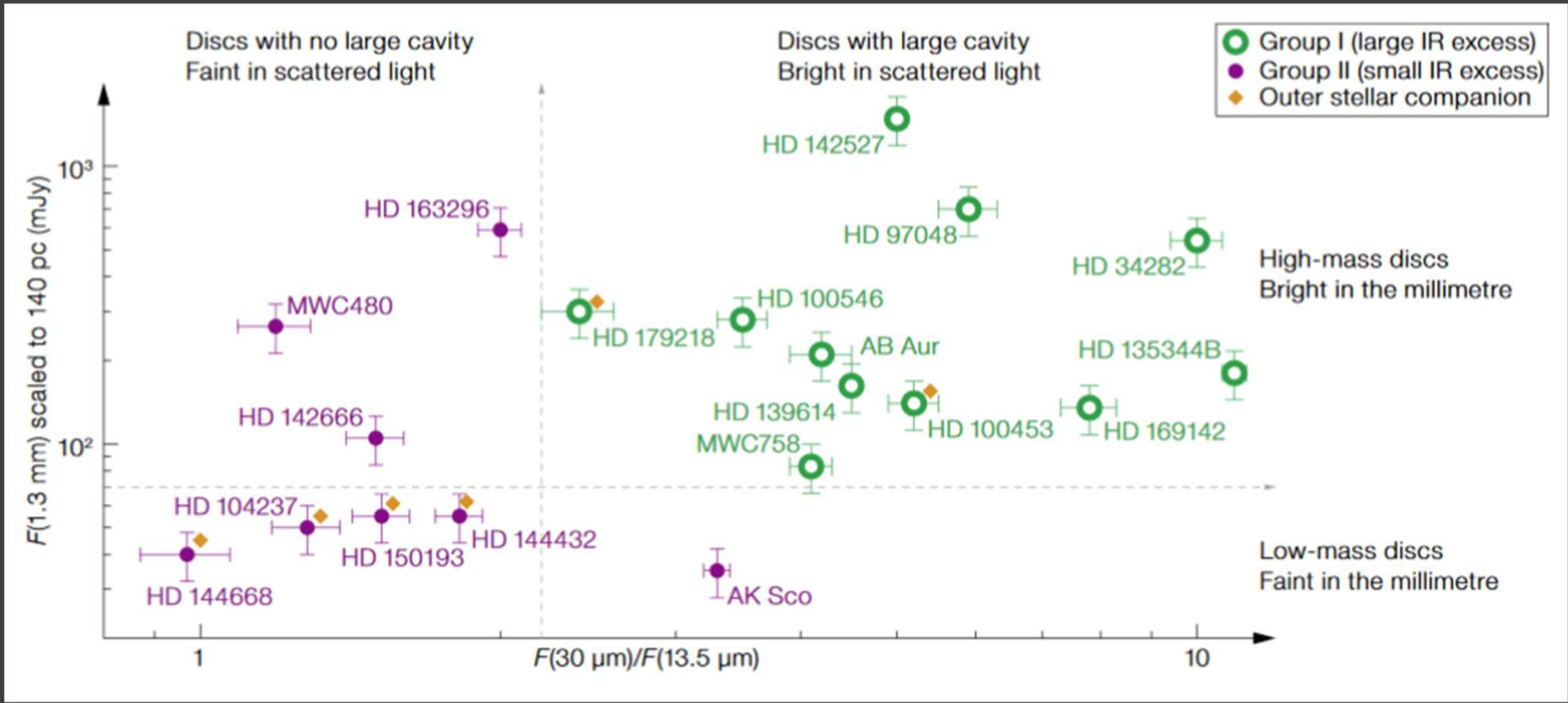


Structures in discs

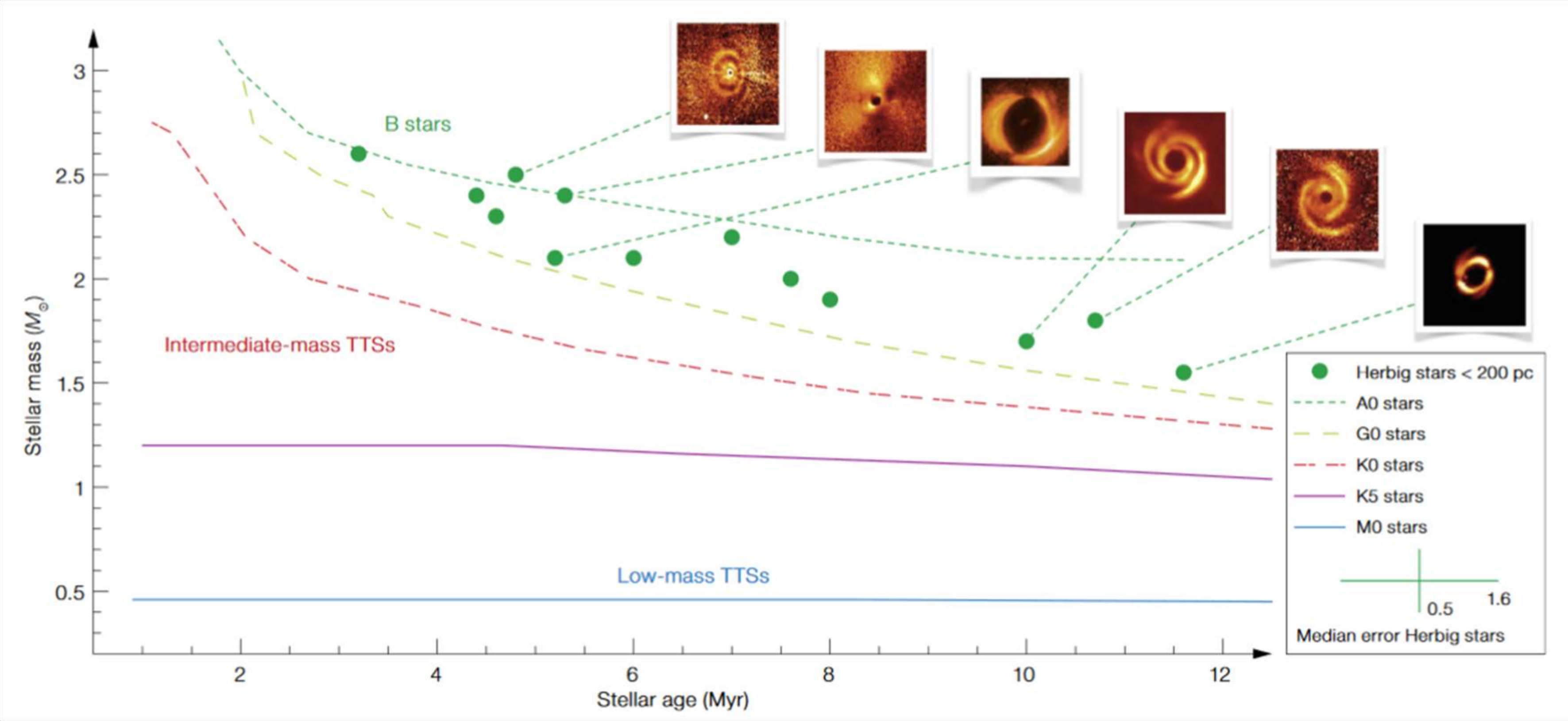


1810.04564, see a review also in 2001.05007

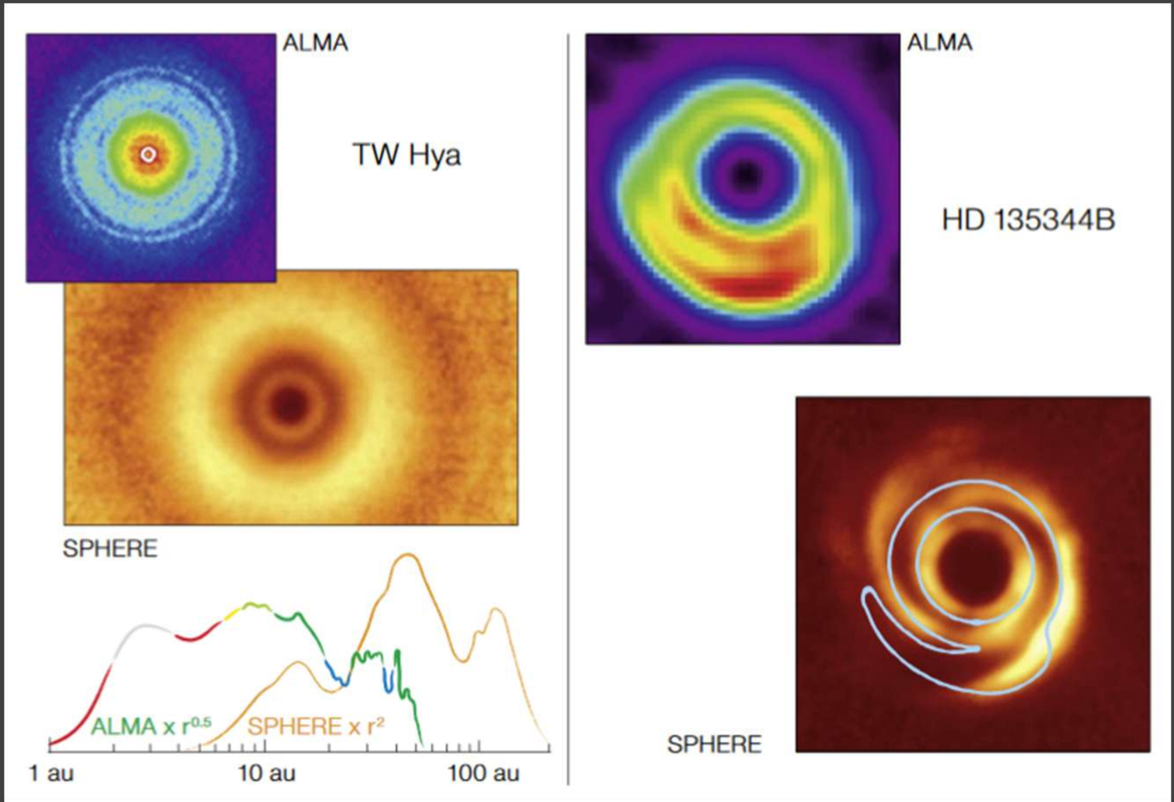
Different discs



Disc evolution

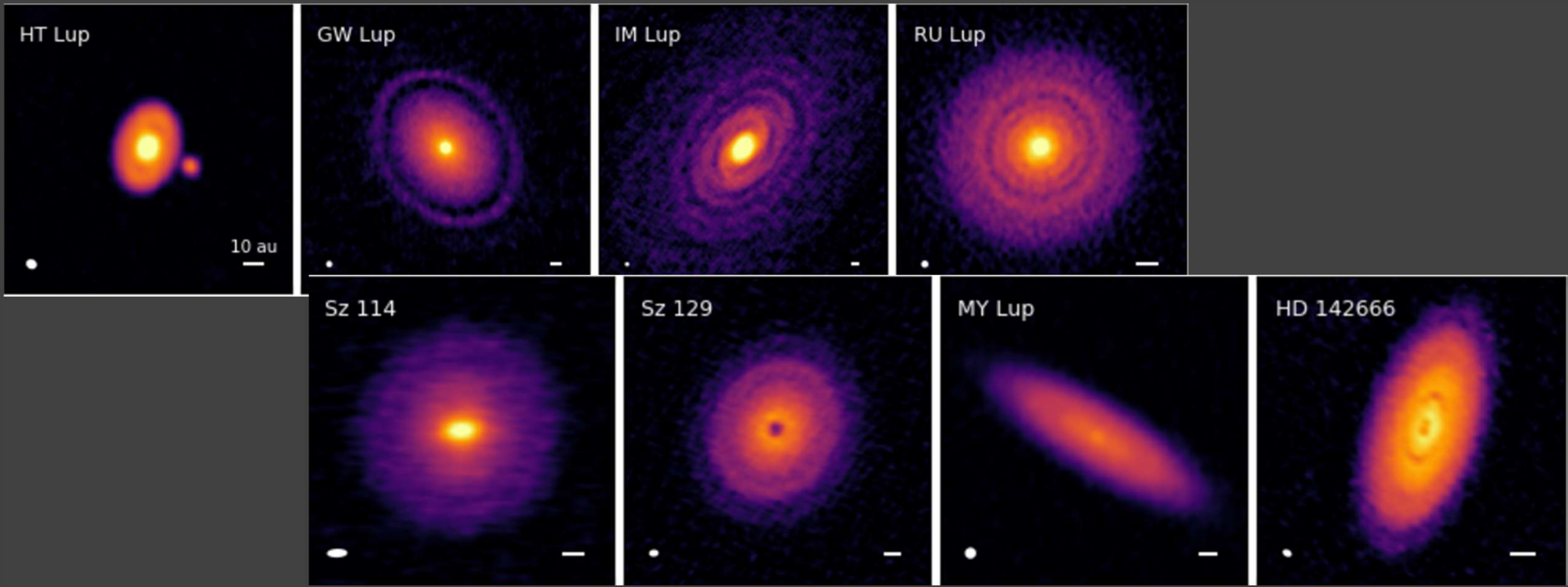


Different wavelengths – different dust

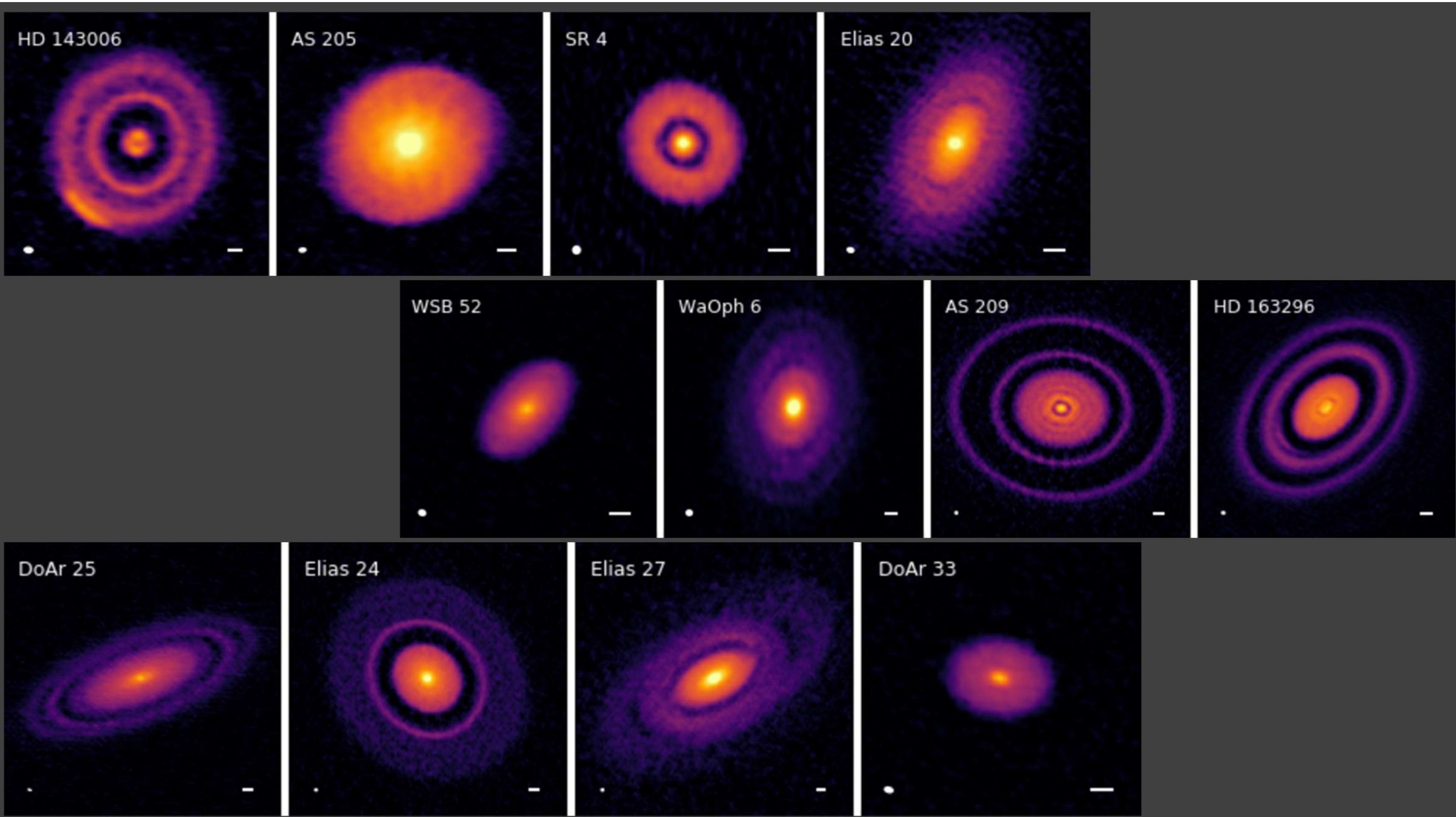


SPHERE – micron grains
ALMA – larger grains

ALMA gallery of discs

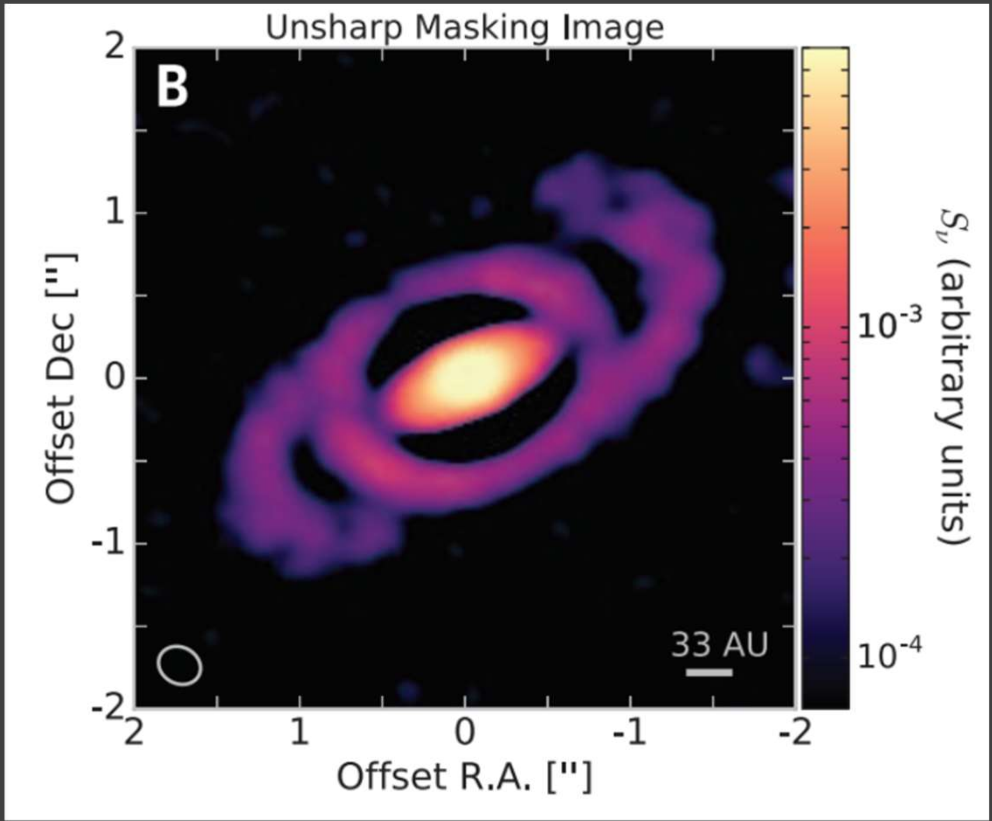


1812.04040



1812.04040, see also the rest of papers in the serie up to 1812.04049

Disc around Elias 2-27



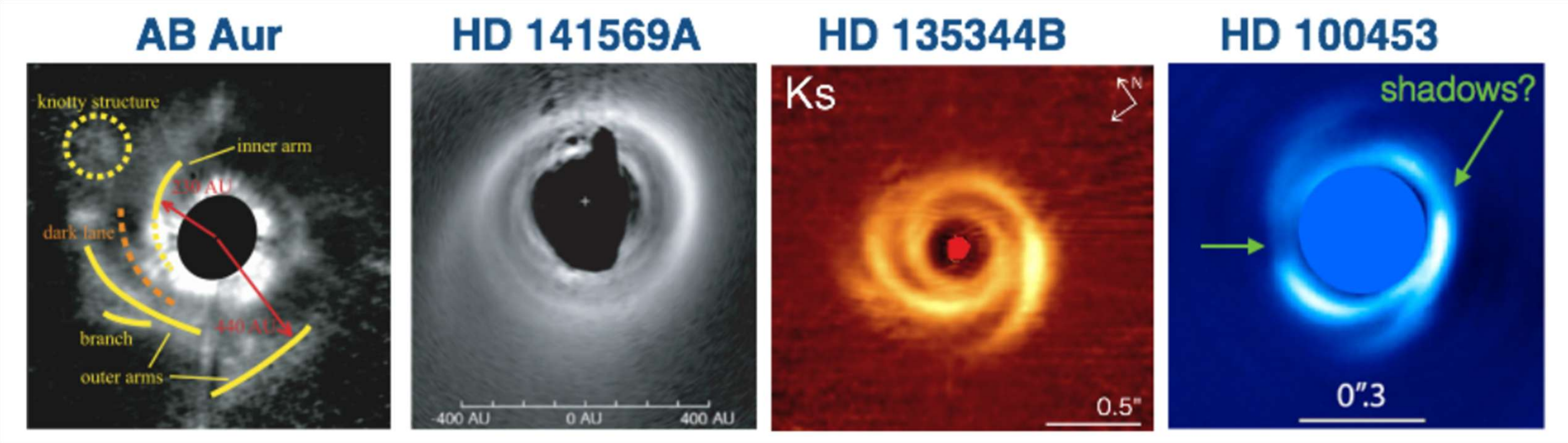
Spiral structure around Elias 2-27
Obtained by ALMA

The star has mass ~0.5 M_{solar},
but a very massive disc (>0.1M_{solar}) around.

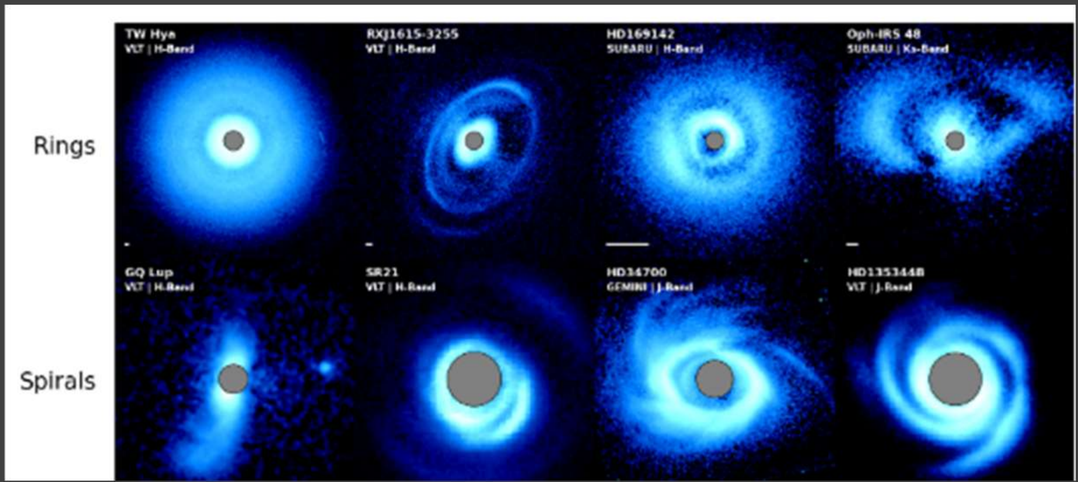
It is important that at distance >10 AU
the disc is transparent for 1.3 mm emission.
So, the spiral patter is related to the matter
also in the disc midplane.

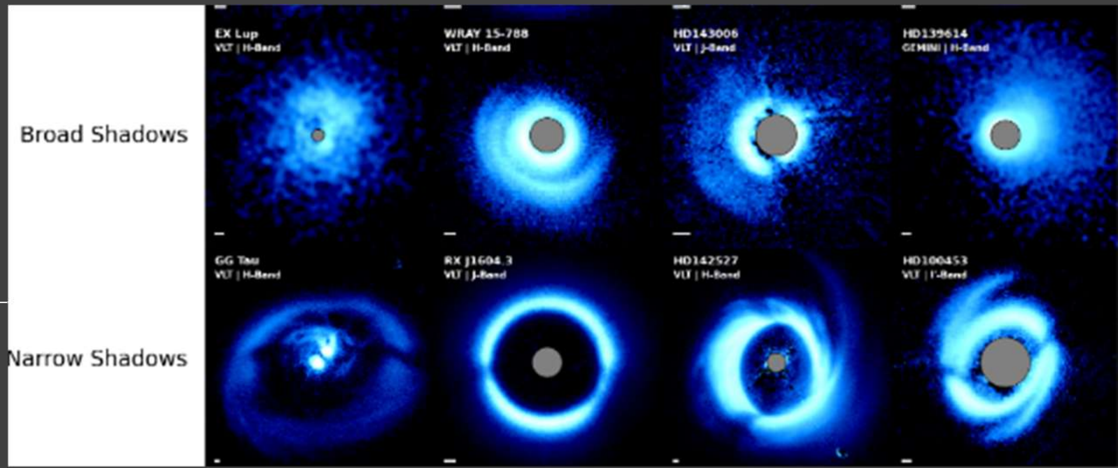
Perez et al. 2016 (1610.05139), taken from the review 1703.08560

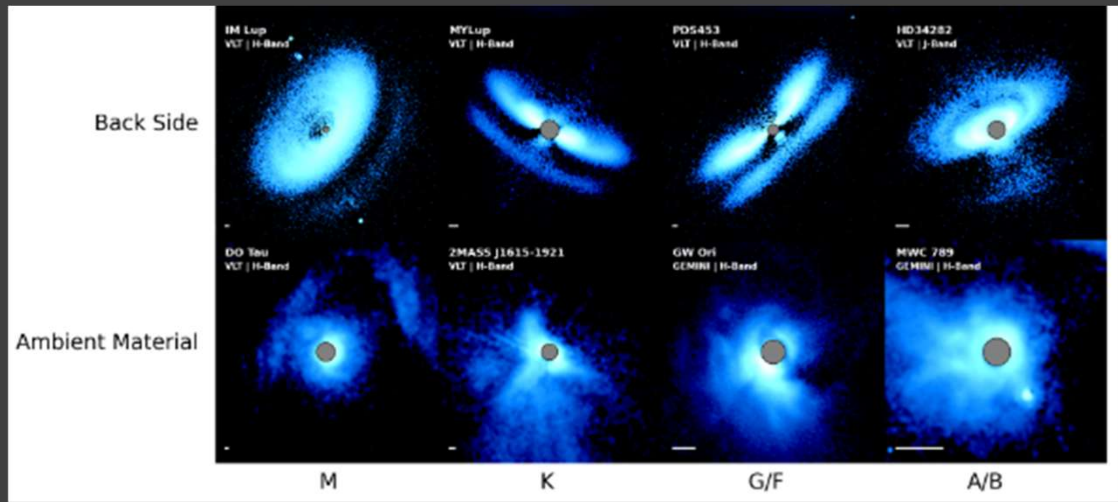
Gallery of spirals



Another gallery



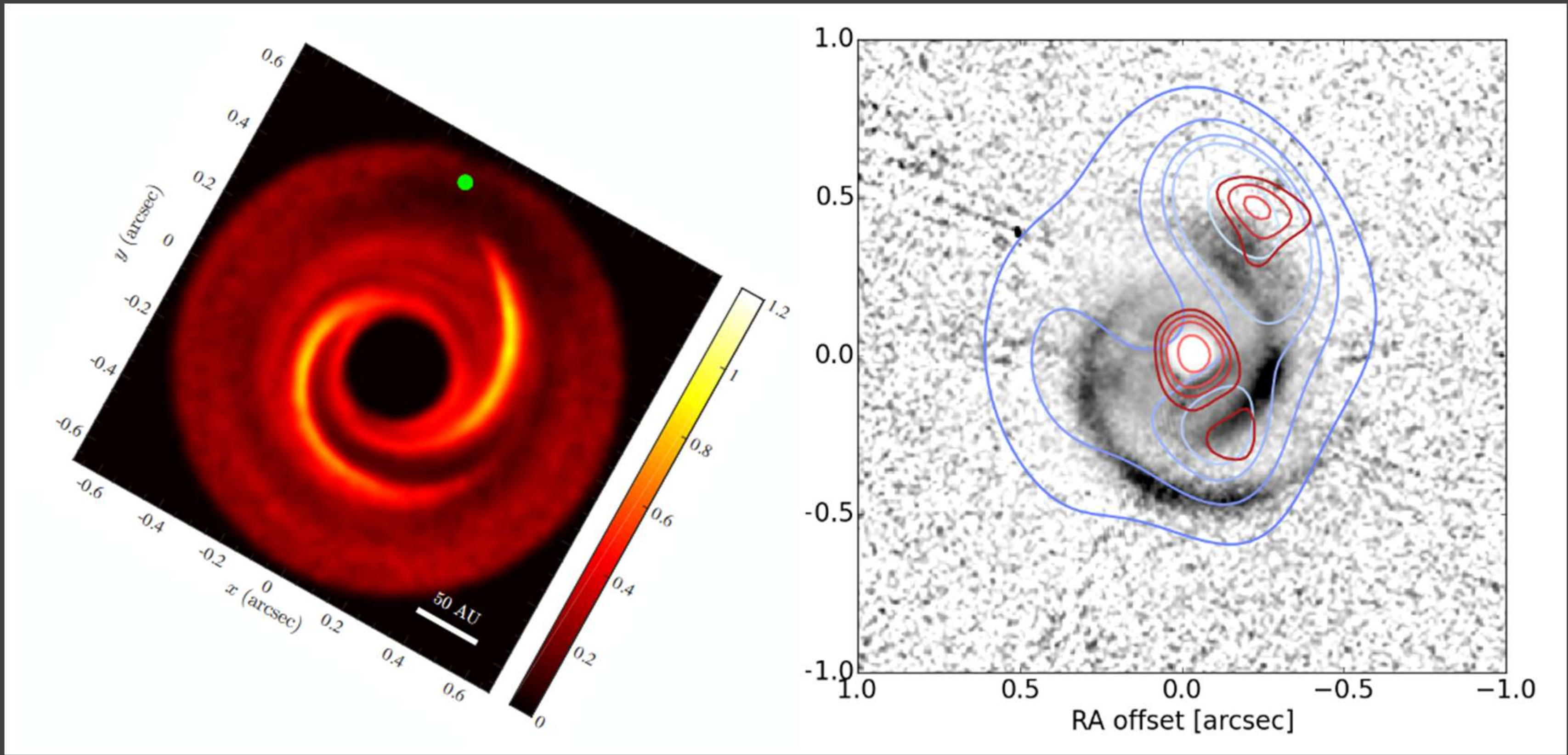




All disks observed with the SPHERE, GPI, and HiCIAO

2203.09991, see more images in this review

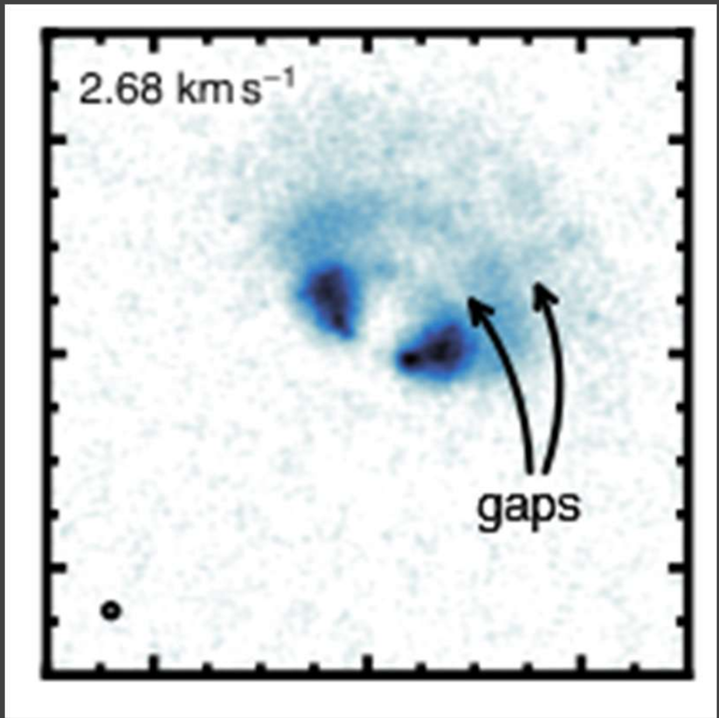
Spirals: model and observations



MWC 758
Left: model
Right: VLA+ALMA+SPHERE

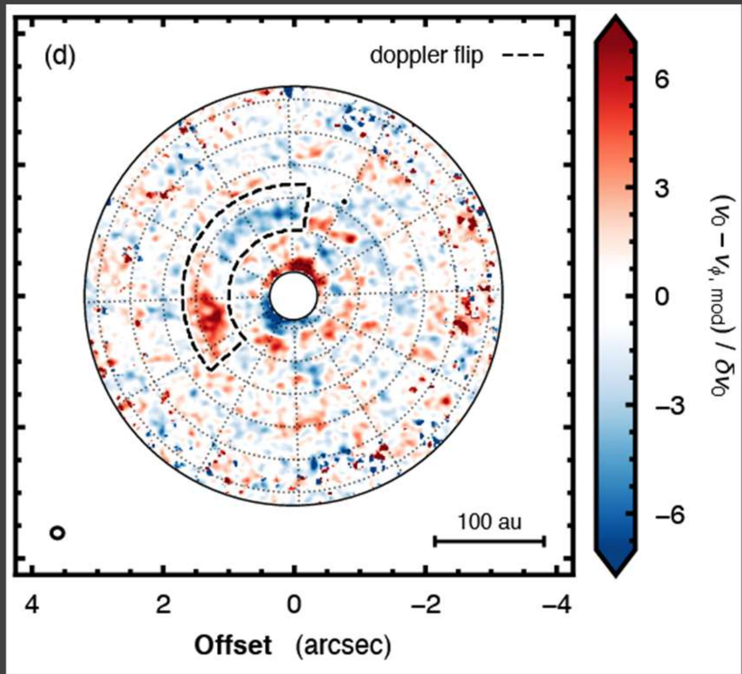
1602.06523, see new data in 1907.06655

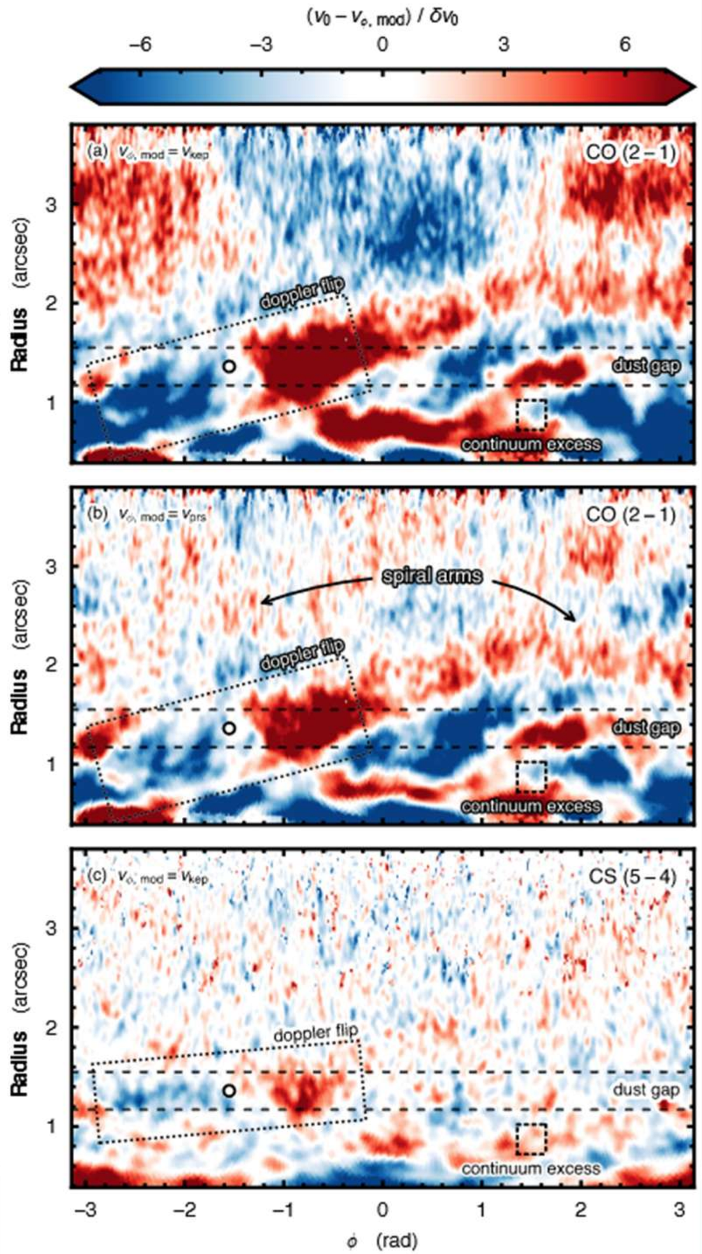
Disc mapping for TW Hydra



CS map

Residual map in CS line

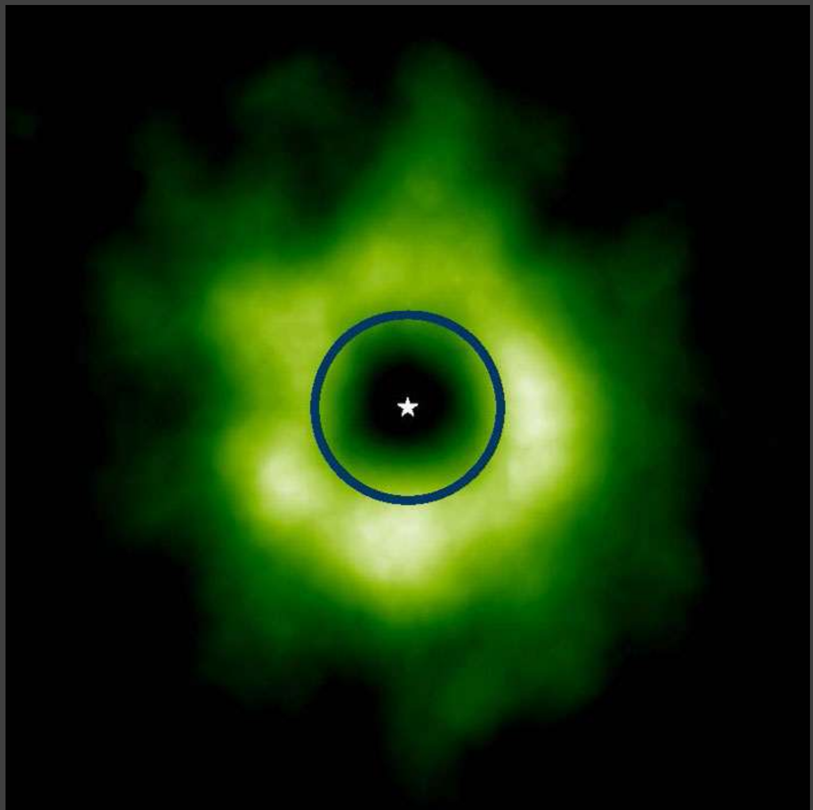


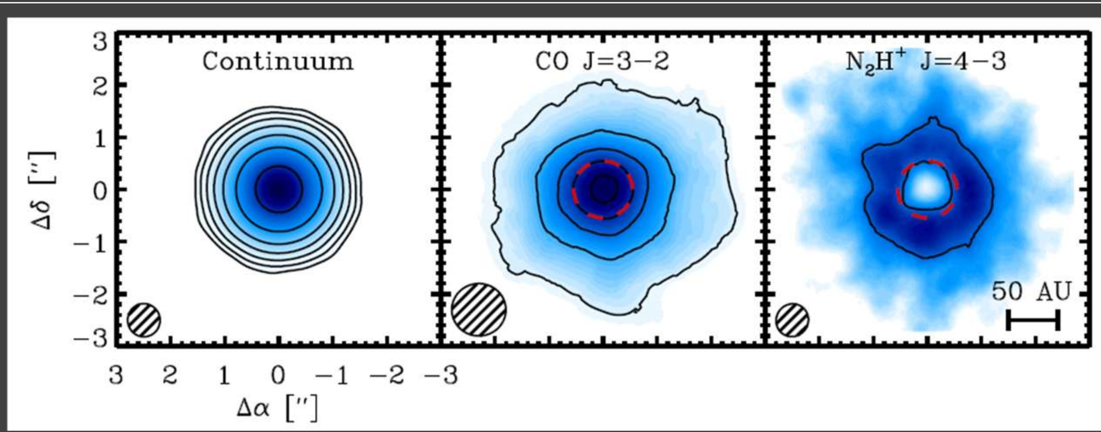


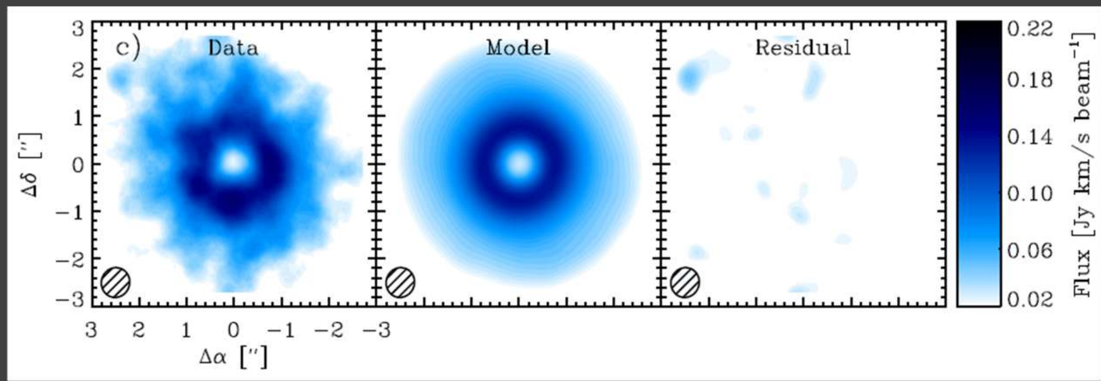
2208.04837

TW Hydra

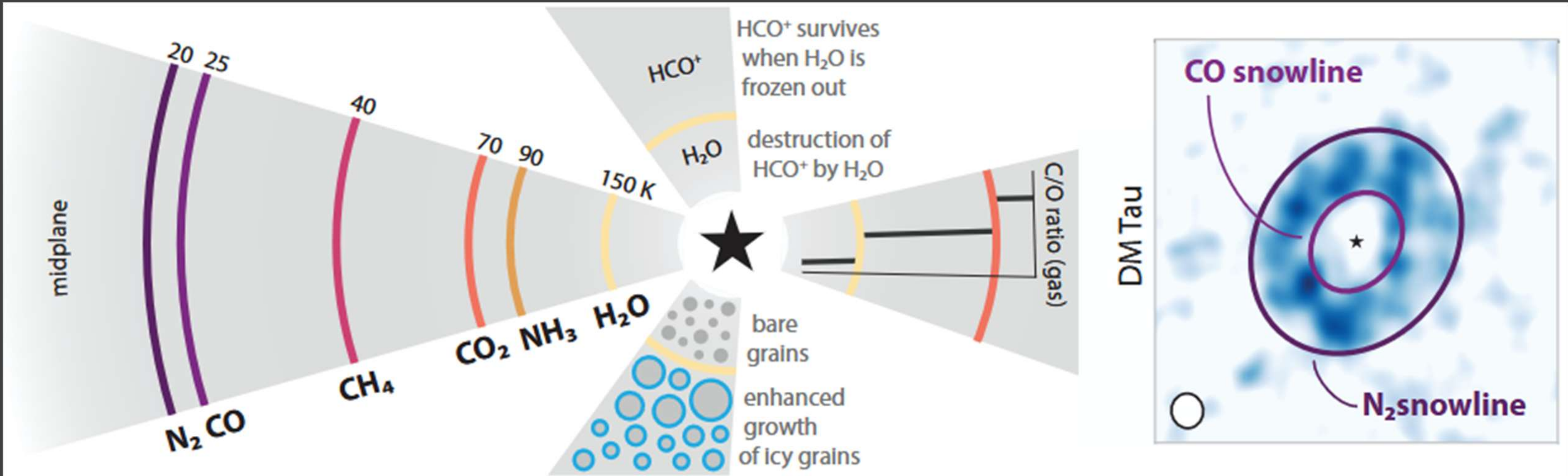
N_2H^+ visible only if CO is frozen out







Snow line



midplane
20
25
40
70
90
150 K
N₂ CO
CH₄
CO₂ NH₃ H₂O
HCO⁺
H₂O
HCO⁺ survives when H₂O is frozen out
destruction of HCO⁺ by H₂O
bare grains
enhanced growth of icy grains
C/O ratio (gas)
DM Tau
CO snowline
N₂snowline

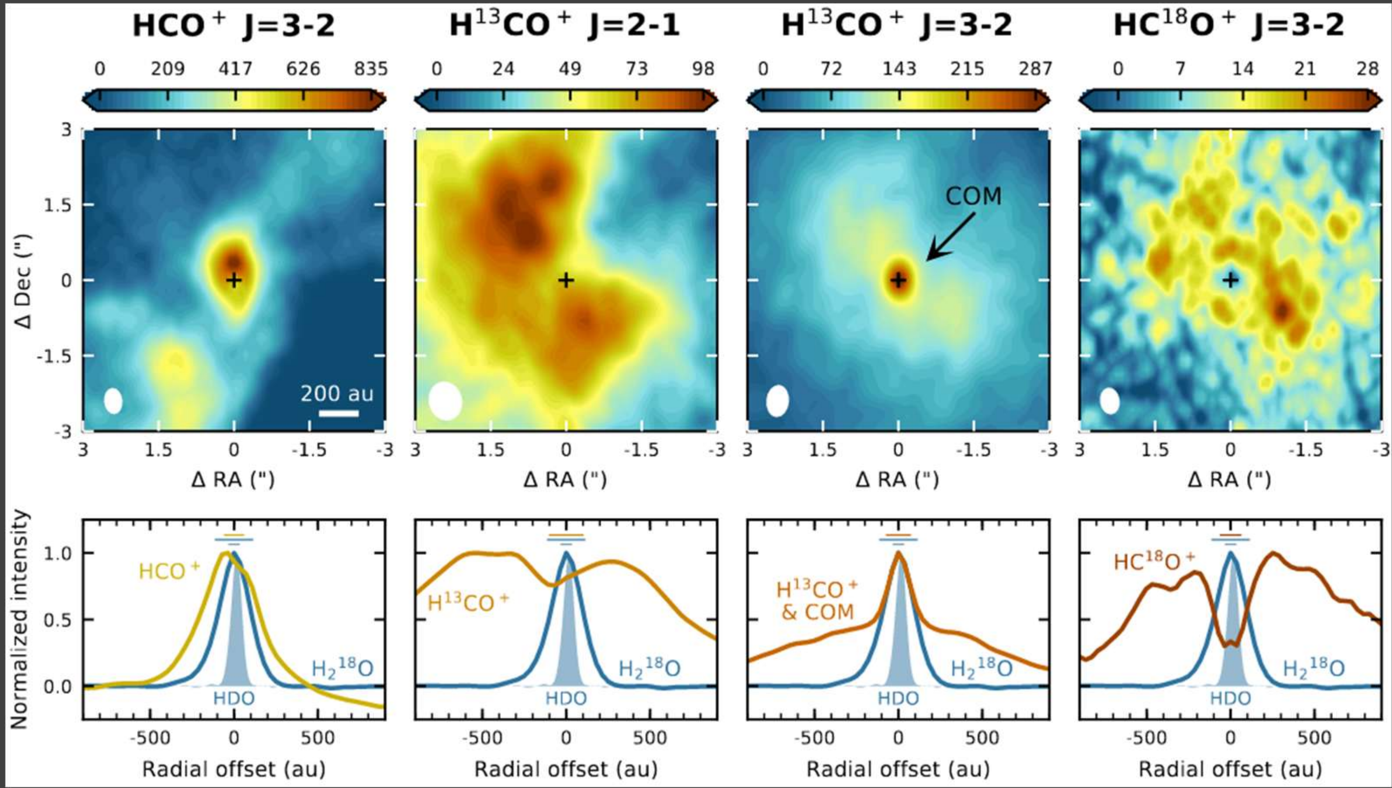
HCO+ as a tracer of the water snowline

Water destroys HCO+ in warm gas.
ALMA observations allow to probe existence of HCO+.

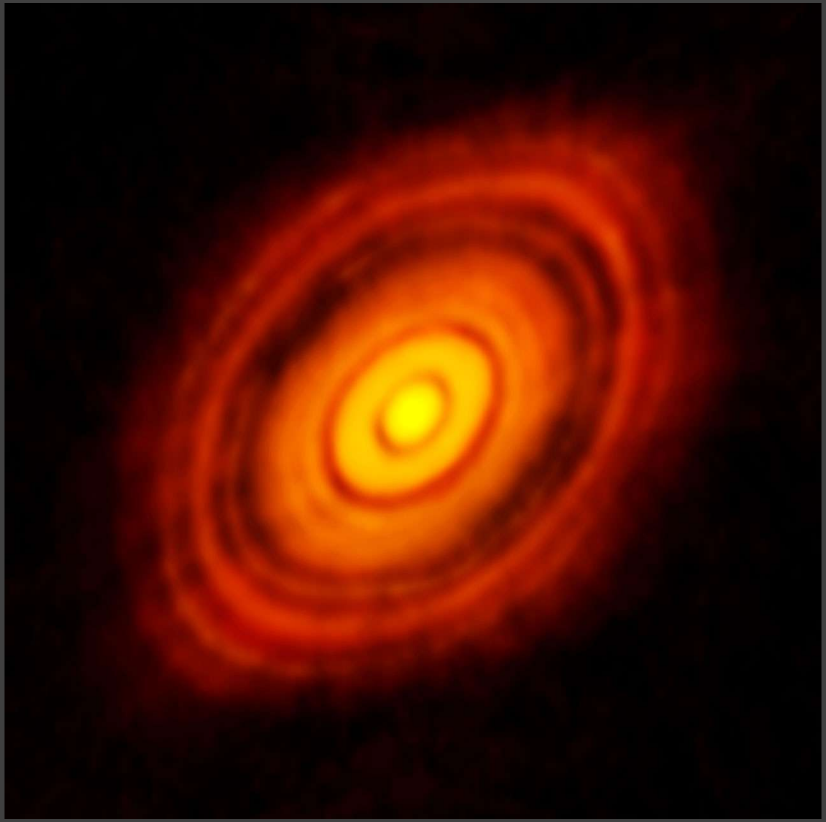
Different isotopes can be used (HCO+, $H^{13}CO+$, $HC^{18}O+$).
Protostars observations are presented.

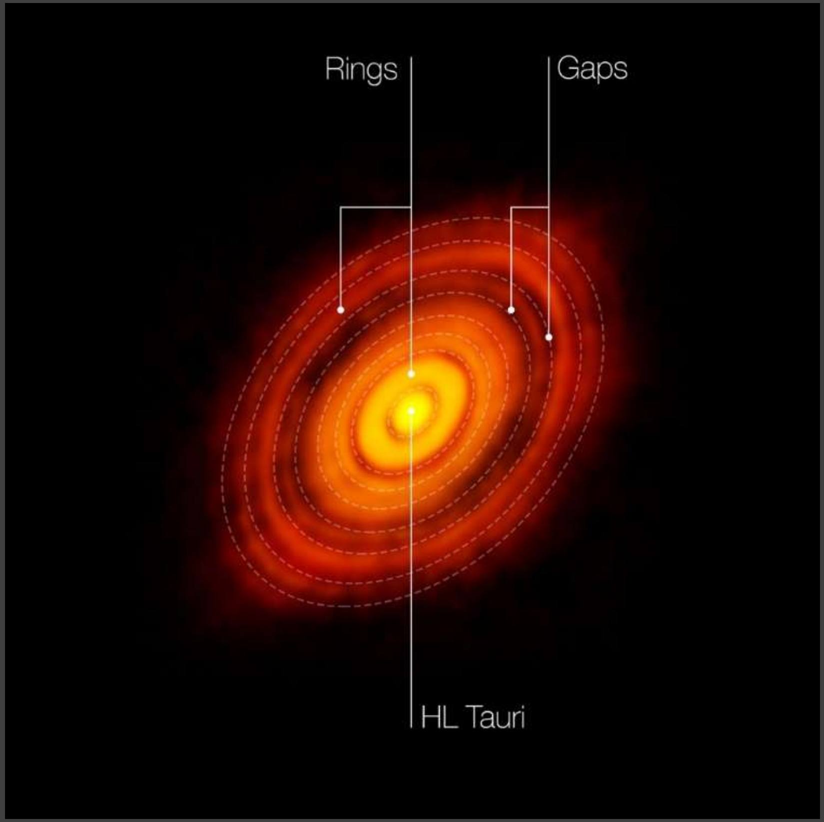
HCO+ is expected to be abundant only in the region where water is frozen out and gaseous CO is available for its formation.

Large size of the snowline is due to accretion bursts in protostellar envelopes.



Protoplanetary disc of HL Tau

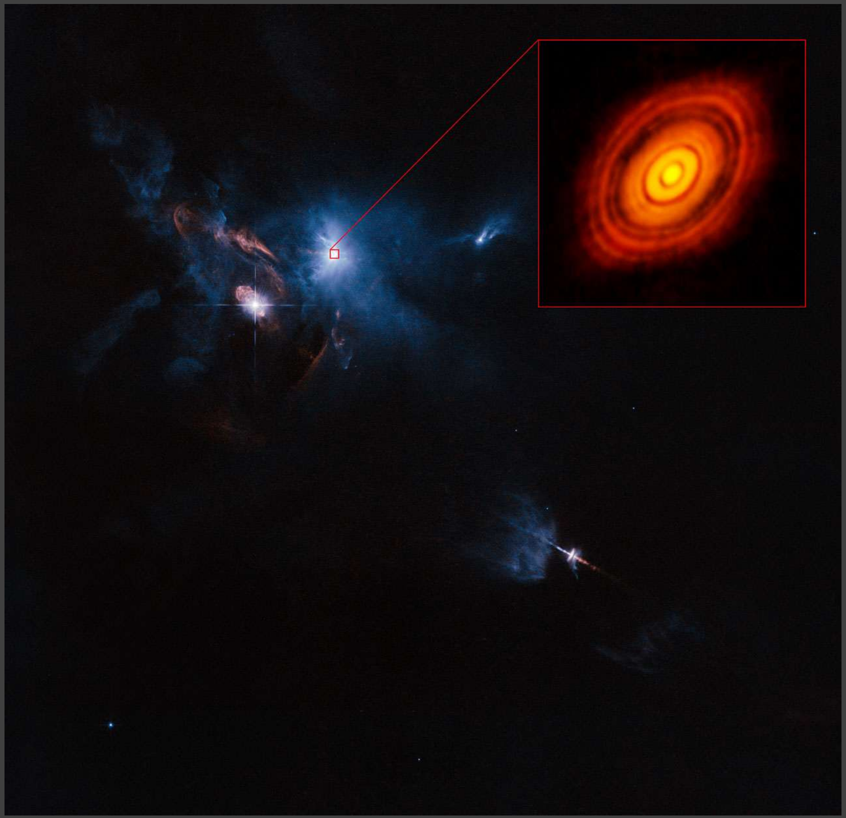




140 pc
Massive disc
Jet
Age <1-2 Myrs

http://www.eso.org/public/images/eso1436a/

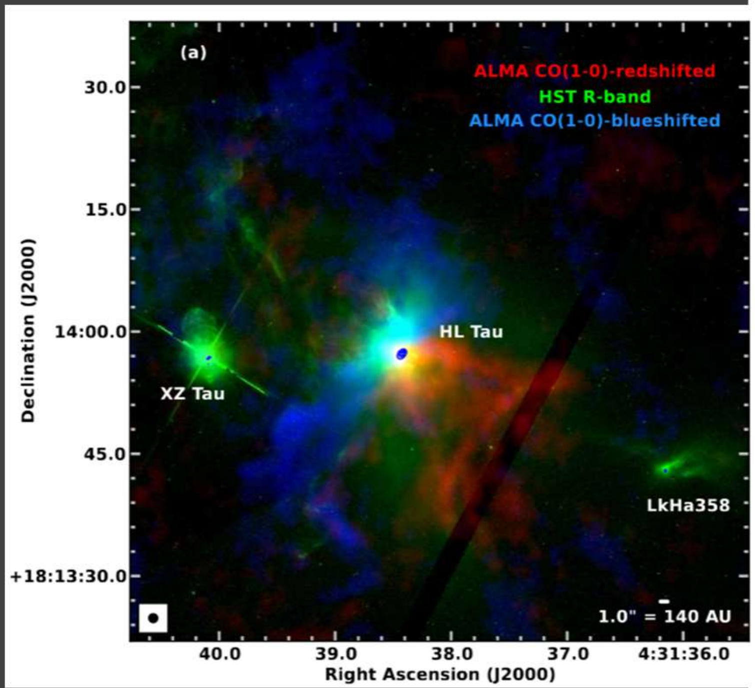
Where stars are born

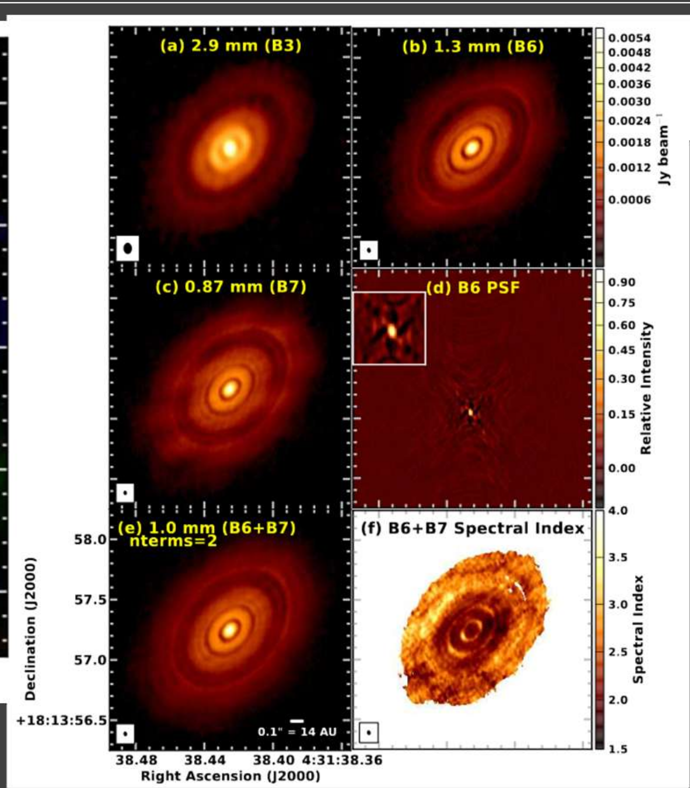


http://www.eso.org/public/images/eso1436b/

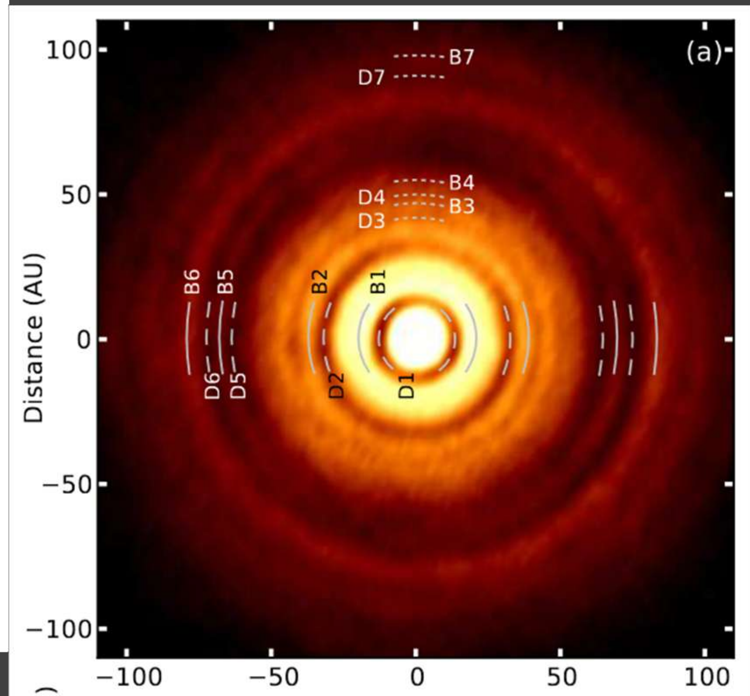
https://public.nrao.edu/AlmaExtras/

More details on the disc of HL Tau

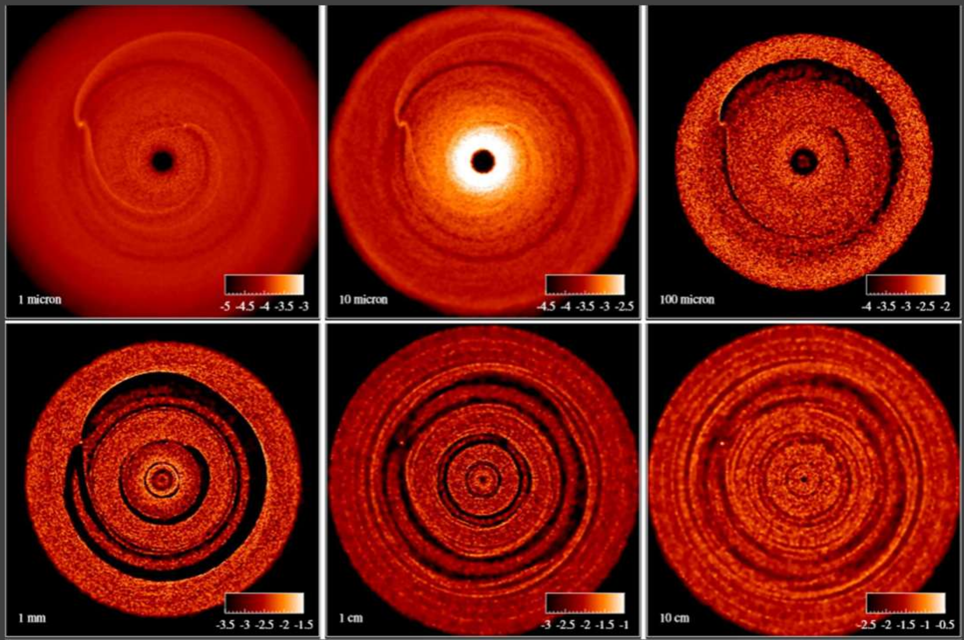




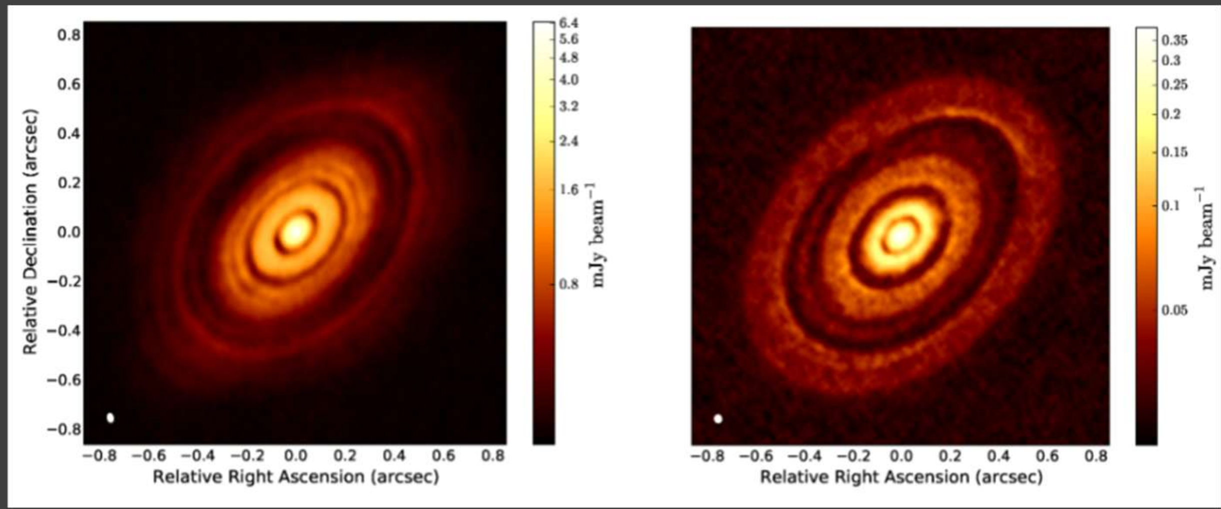
Some rings are in resonance with each other.



Modeling of the HL Tau disc



Three planets with masses from 0.2 up to 0.55 Jupiter mass

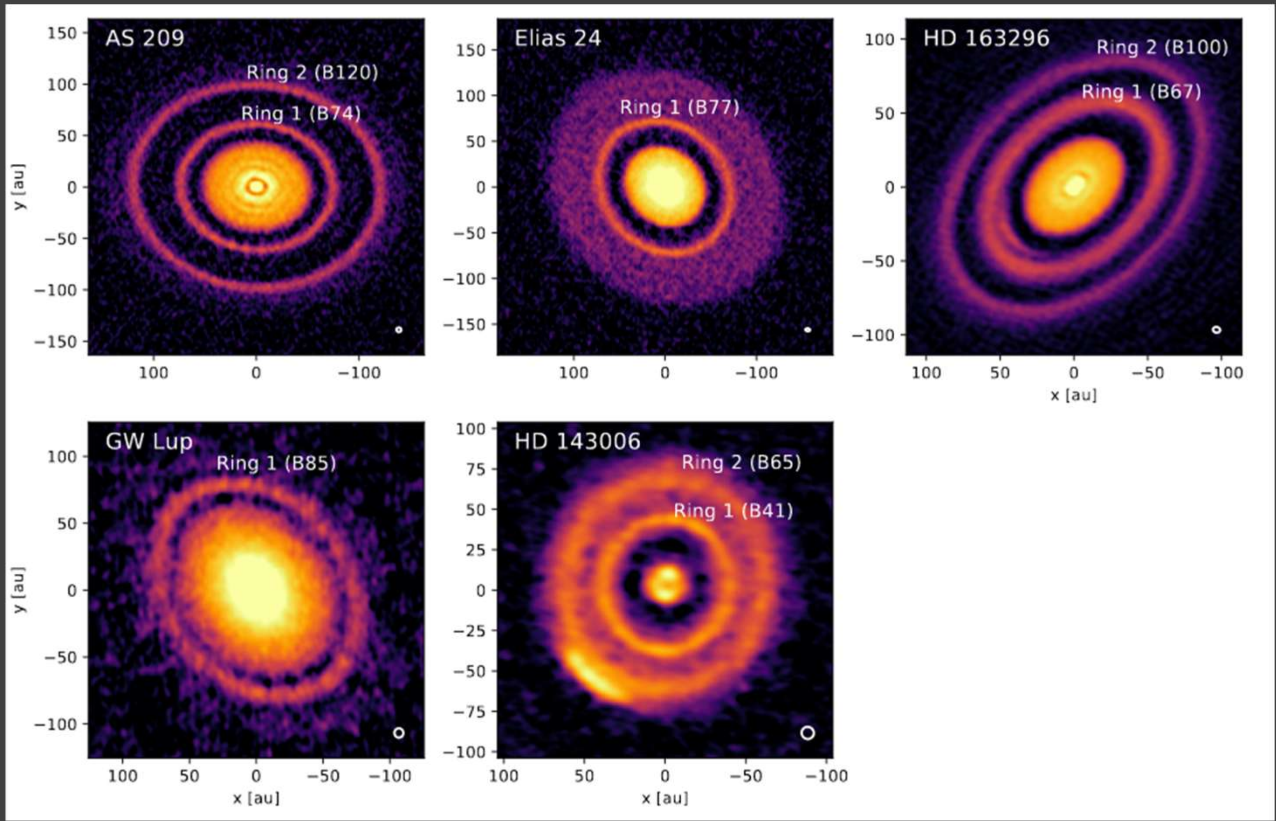


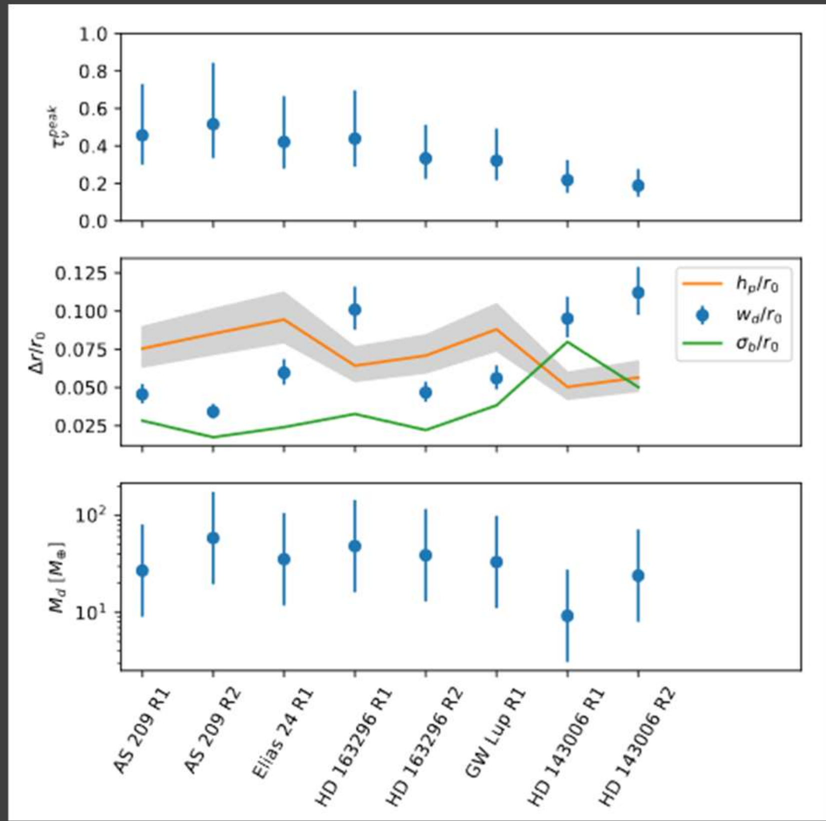
Observations

Modeling

1507.06719

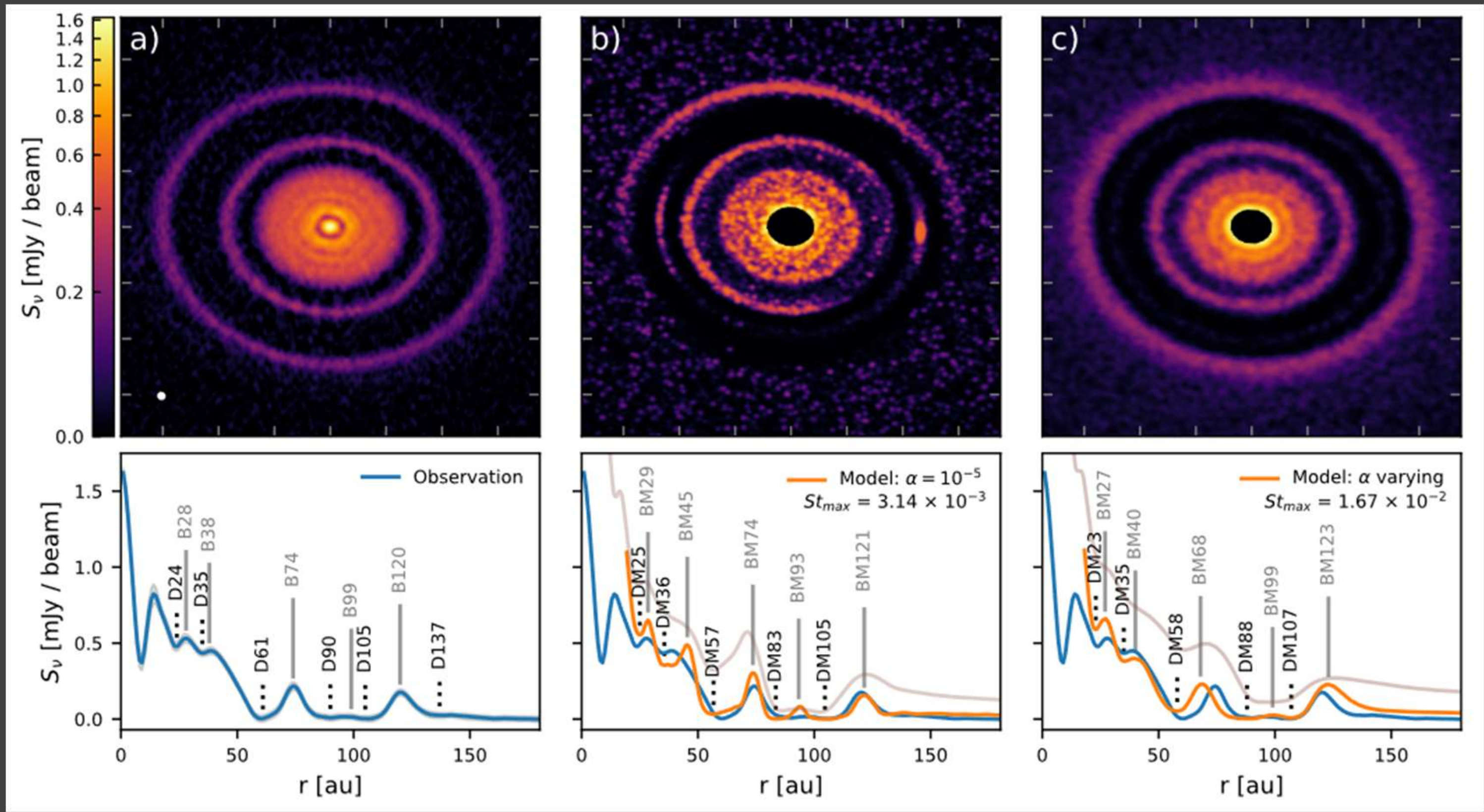
More rings from ALMA





1812.04044

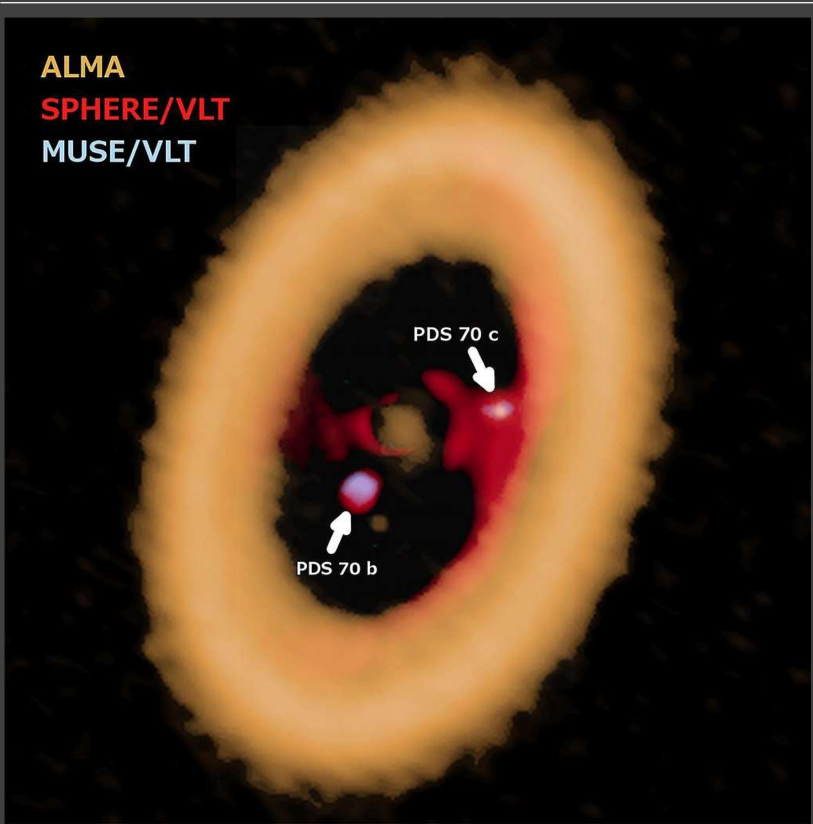
Modeling ring structure. Planets

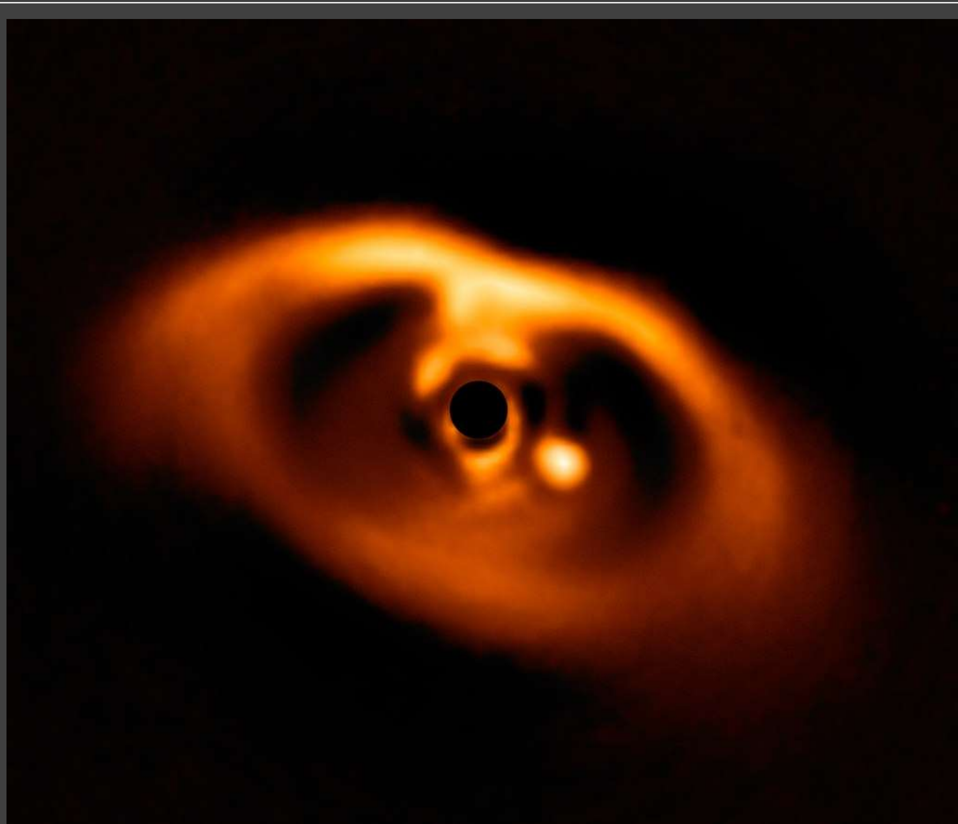


One planet at 99 au.

A) Observations
B) Model. Constant alpha
C) Model. Varying alpha.

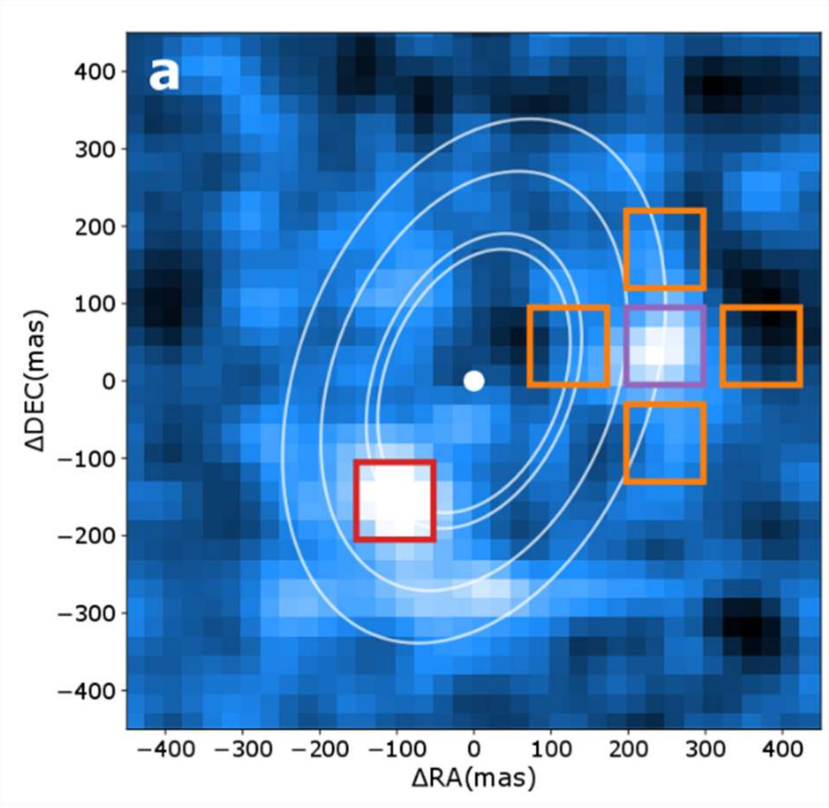
PDS 70: two planets in a disc





Wikipedia

PDS 70. The second planet



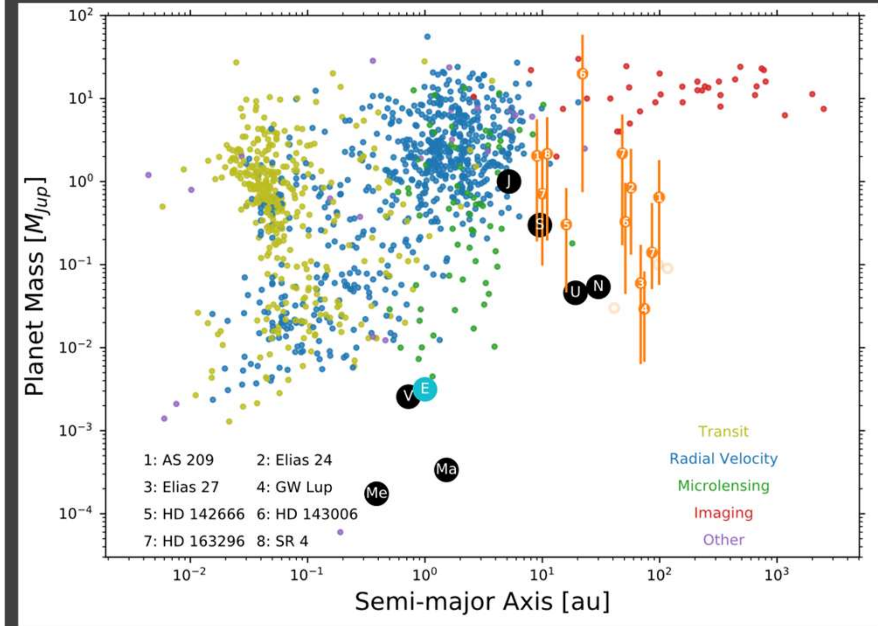
VLT observations

MUSE (Multi Unit Spectroscopic Explorer)

Halpha image

Properties of (invisible) planets

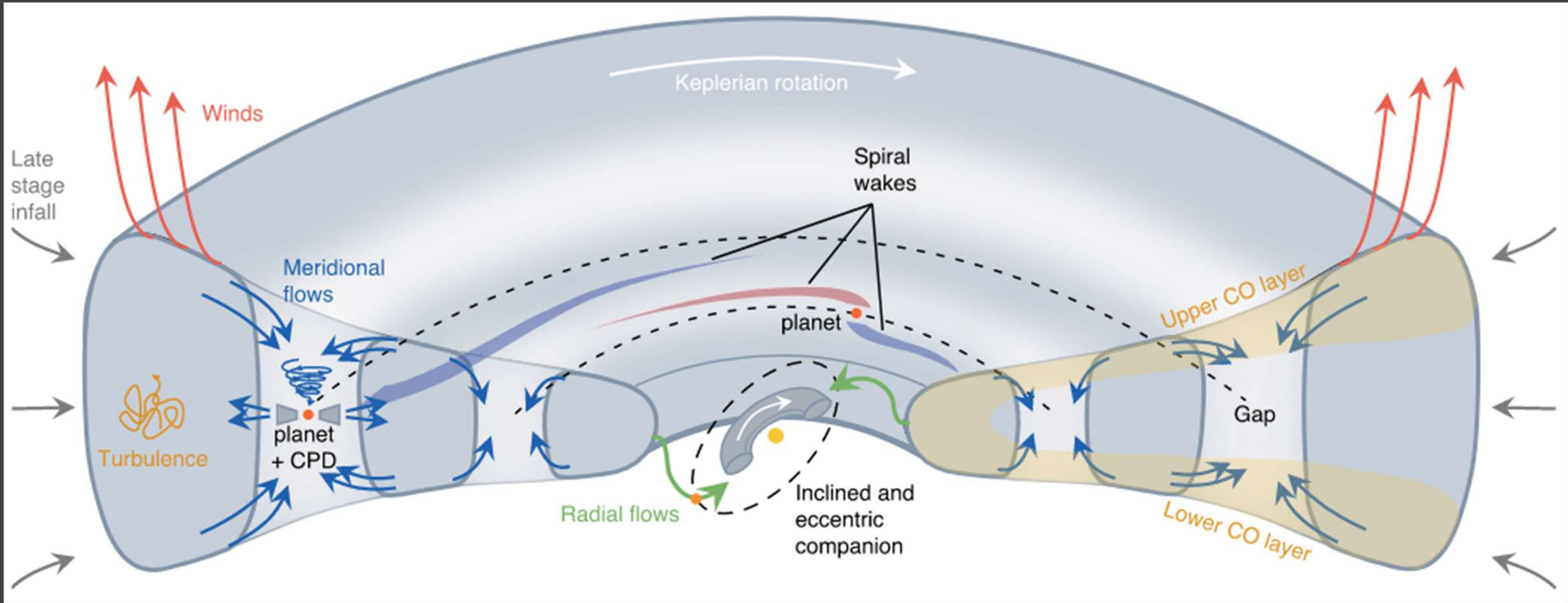
Name (1)	M_* ($M_\odot$) (2)	r_{gap} (au) (3)	width (Δ) (4)	$M_{p,am4}$ (M_{Jup}) (11)	$M_{p,am3}$ (M_{Jup}) (12)	$M_{p,am2}$ (M_{Jup}) (13)	Uncertainty ($log_{10}(M_p)$) (14)
AS 209	0.83	9	0.42	1.00, 0.81, 0.37	2.05, 1.66, 0.76	4.18, 3.38, 1.56	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
AS 209	0.83	99	0.31	0.32, 0.18, –	0.65, 0.37, –	1.32, 0.75, –	$^{+0.14}_{-0.17}$, $^{+0.21}_{-0.50}$, –
Elias 24	0.78	57	0.32	0.41, 0.19 –	0.84, 0.40, –	1.72, 0.81, –	$^{+0.16}_{-0.14}$, $^{+0.22}_{-0.16}$, –
Elias 27	0.49	69	0.18	0.03, 0.02, –	0.06, 0.05, –	0.12, 0.10, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
GW Lup*	0.46	74	0.15	0.01, –, –	0.03, –, –	0.06, –, –	$^{+0.14}_{-0.17}$, –, –
HD 142666	1.58	16	0.20	0.15, 0.12, 0.09	0.30, 0.25, 0.19	0.62, 0.50, 0.38	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
HD 143006	1.78	22	0.62	9.75, 2.35, –	19.91, 4.80, –	40.64, 9.81, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
HD 143006	1.78	51	0.22	0.16, 0.14 –	0.33, 0.28, –	0.67, 0.57, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
HD 163296	2.04	10	0.24	0.35, 0.28, 0.19	0.71, 0.58, 0.39	1.46, 1.18, 0.79	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
HD 163296	2.04	48	0.34	1.07, 0.54, –	2.18, 1.10, –	4.45, 2.24, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
HD 163296	2.04	86	0.17	0.07, 0.08, –	0.14, 0.16, –	0.29, 0.34, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
SR 4	0.68	11	0.45	1.06, 0.86, 0.38	2.16, 1.75, 0.77	4.41, 3.57, 1.57	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
DoAr 25*	0.95	98	0.15	(– , 0.10, –)	(0.10, –, –)	(– , 0.95, –)	–, –, –
DoAr 25	0.95	125	0.08	(0.03, –, –)	– , –, –	– , –, –	–, –, –
Elias 20	0.48	25	0.13	–, –, –	(0.05, 0.05, 0.05)	– , –, –	–, –, –
IM Lup	0.89	117	0.13	(0.09 , –, –)	(0.09, –, –)	–, – , –	–, –, –
RU Lup	0.63	29	0.14	(0.07, –, –)	(–, 0.07, 0.07)	– , –	–, –, –
Sz 114	0.17	39	0.12	(0.02 , 0.02, –)	–, –, –	–, – , –	–, –, –
Sz 129	0.83	41	0.08	(–, 0.03 , –)	(0.03, –, –)	–, – , –	–, –, –



Three values of planet mass for each alpha correspond to different models of dust size.

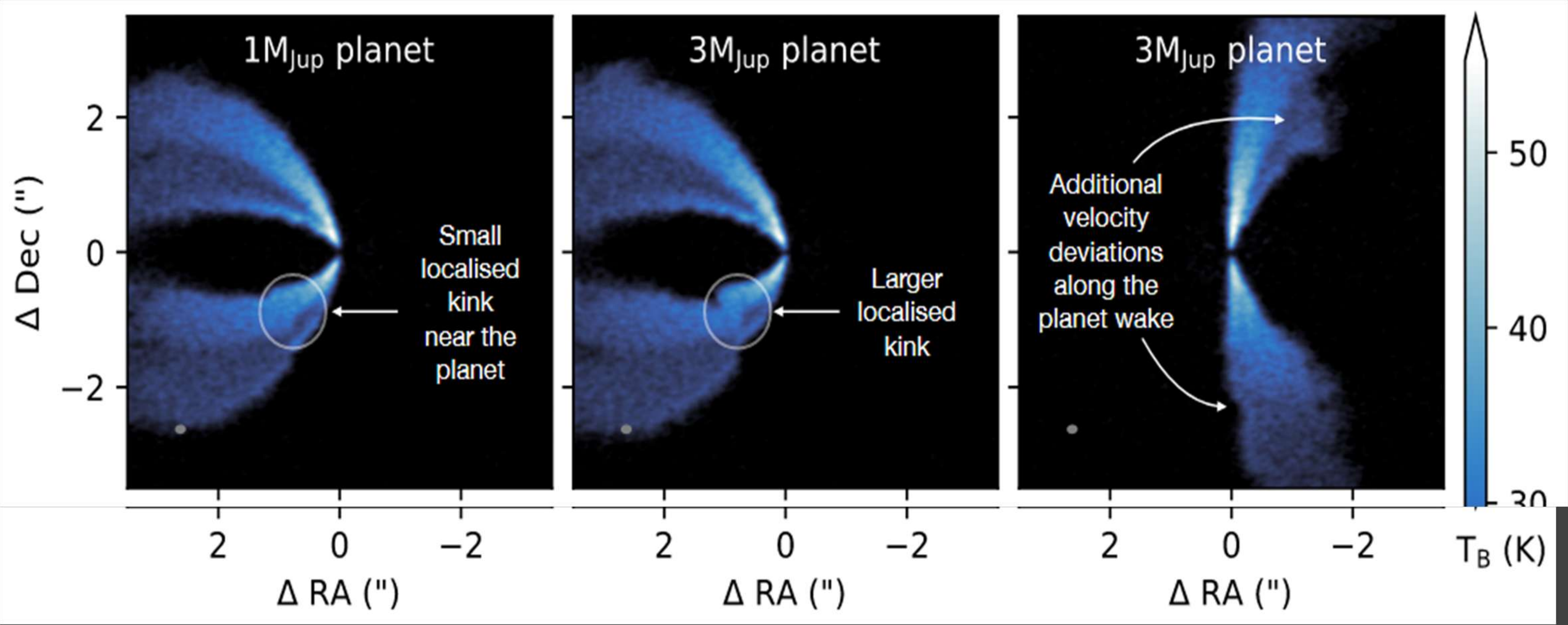
1812.04045

Disc structure with spirals, etc.

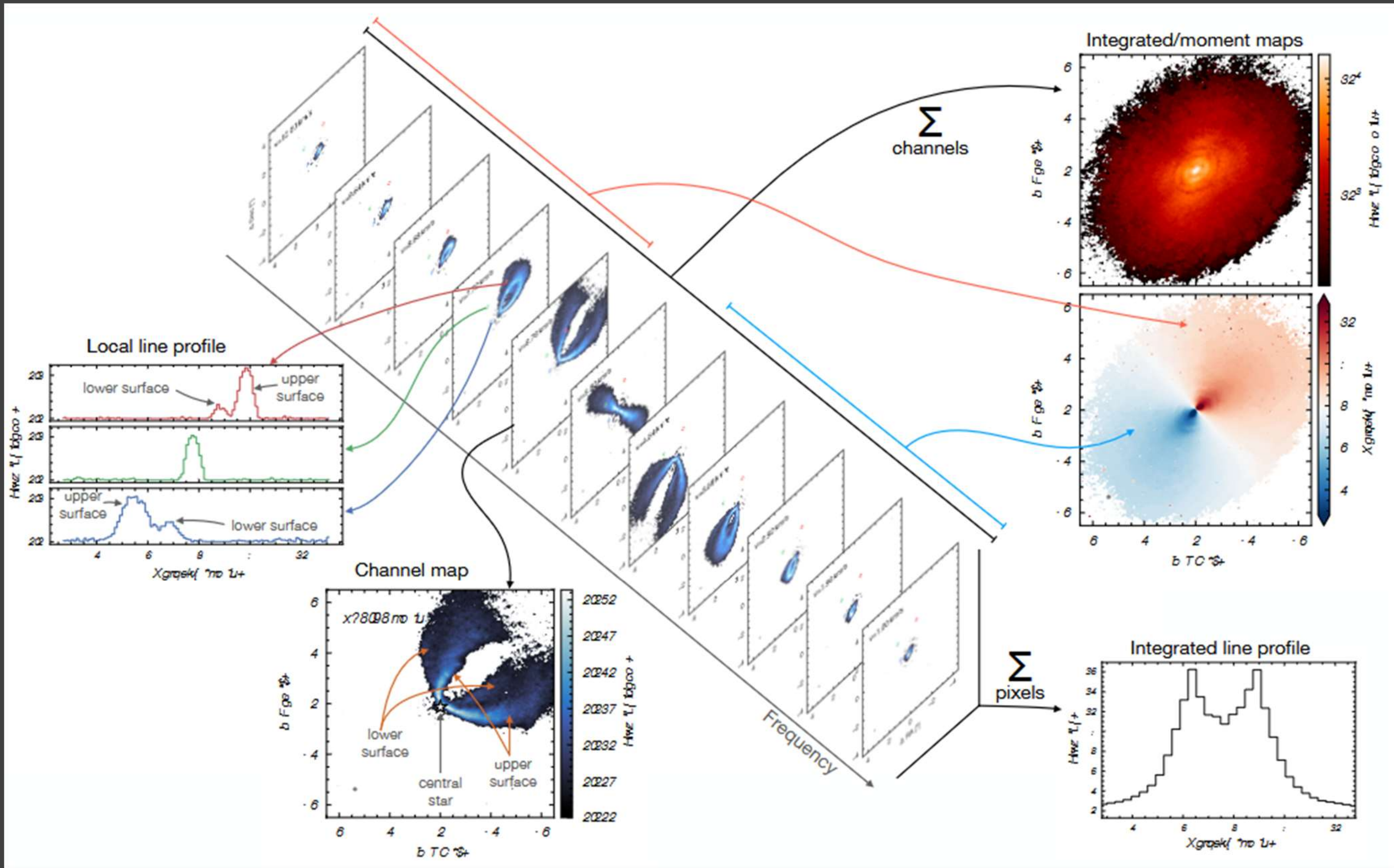


See a review in 2203.09528

Modeling of kinematic structures (CO maps)



2203.09528

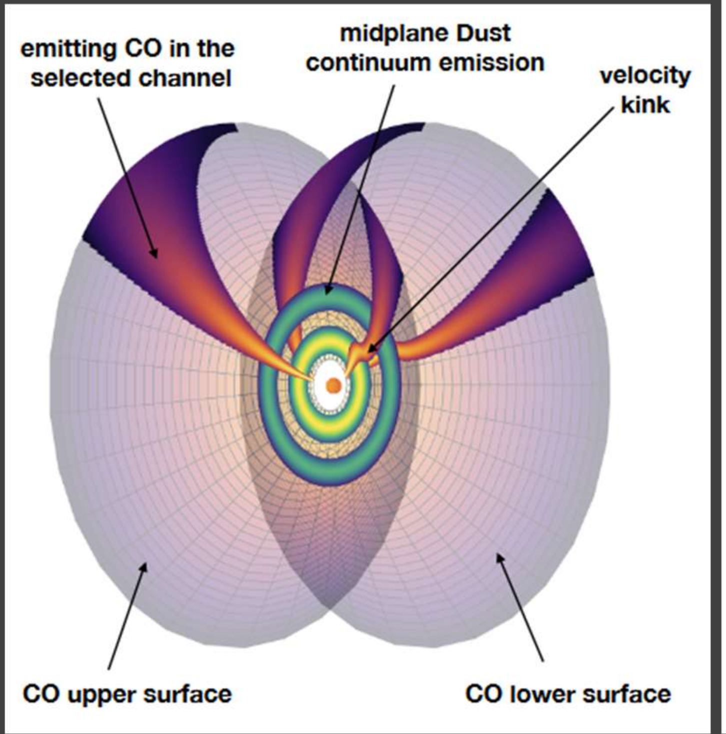


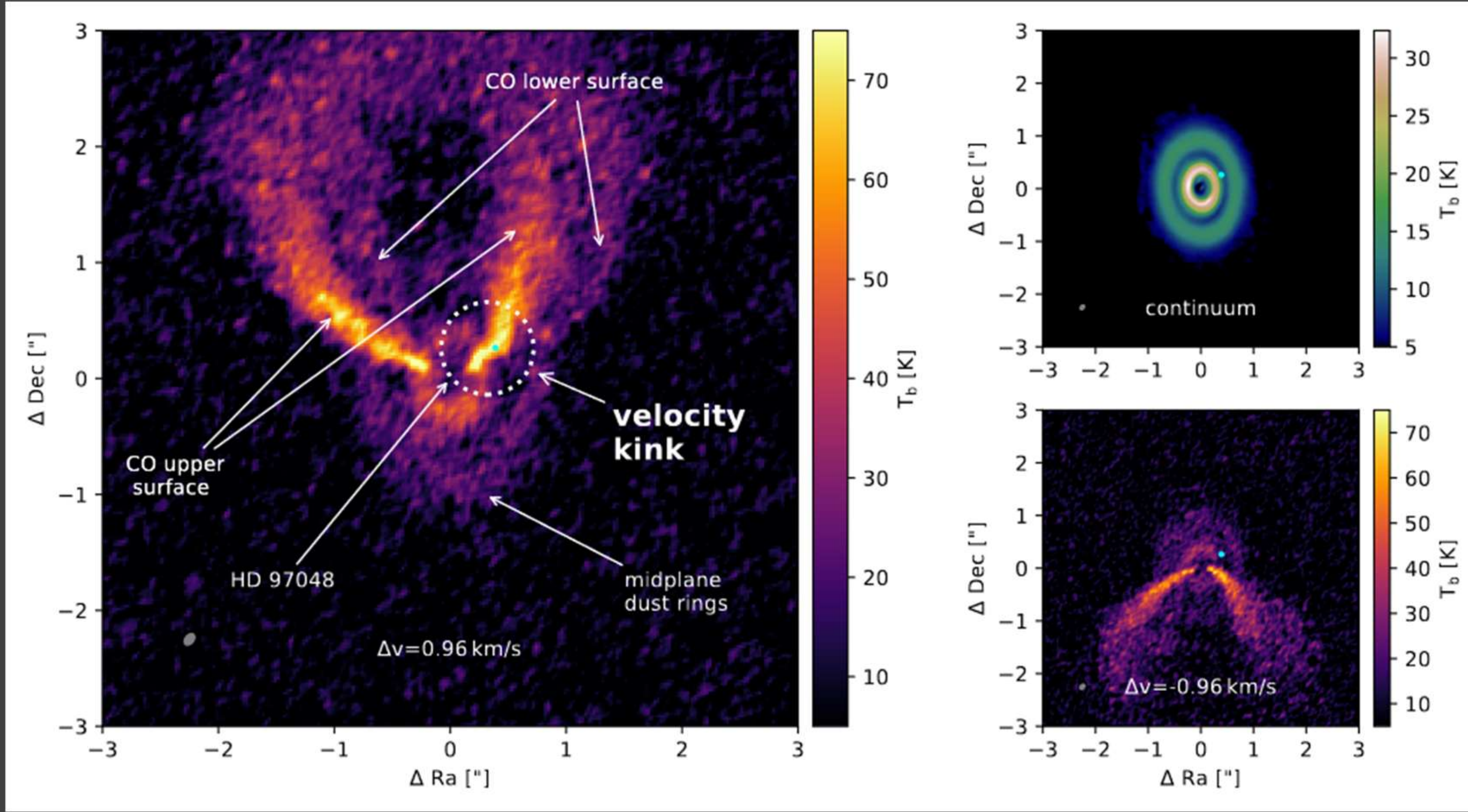
Integrated/moment maps
Σ
channels
Local line profile
lower surface
upper surface
upper surface
lower surface
Channel map
lower surface
central star
upper surface
Frequency
Σ
pixels
Integrated line profile

2203.09528

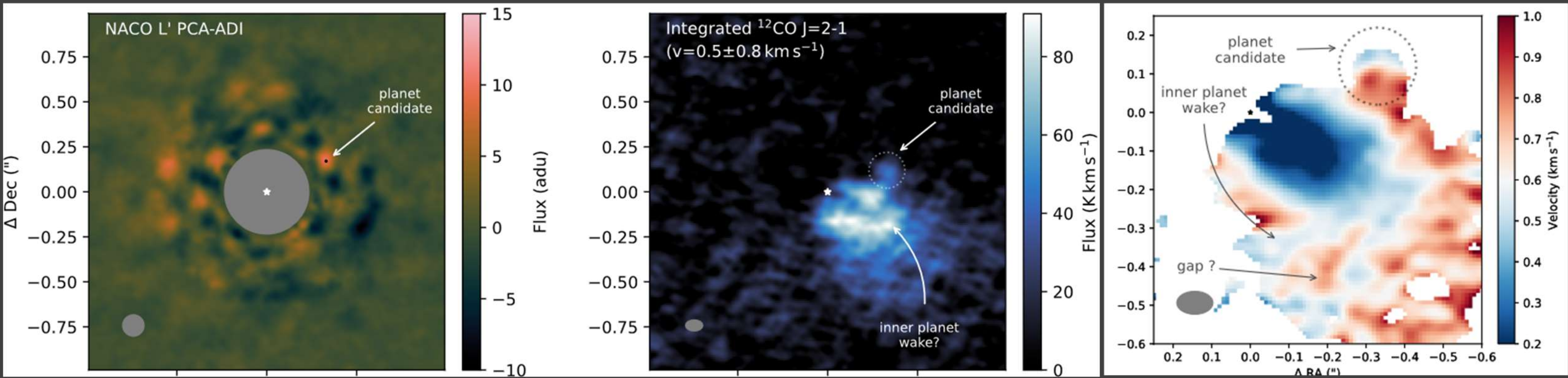
Kinematic detection of a planet HD 97048

Gap + disturbance in the gas flow



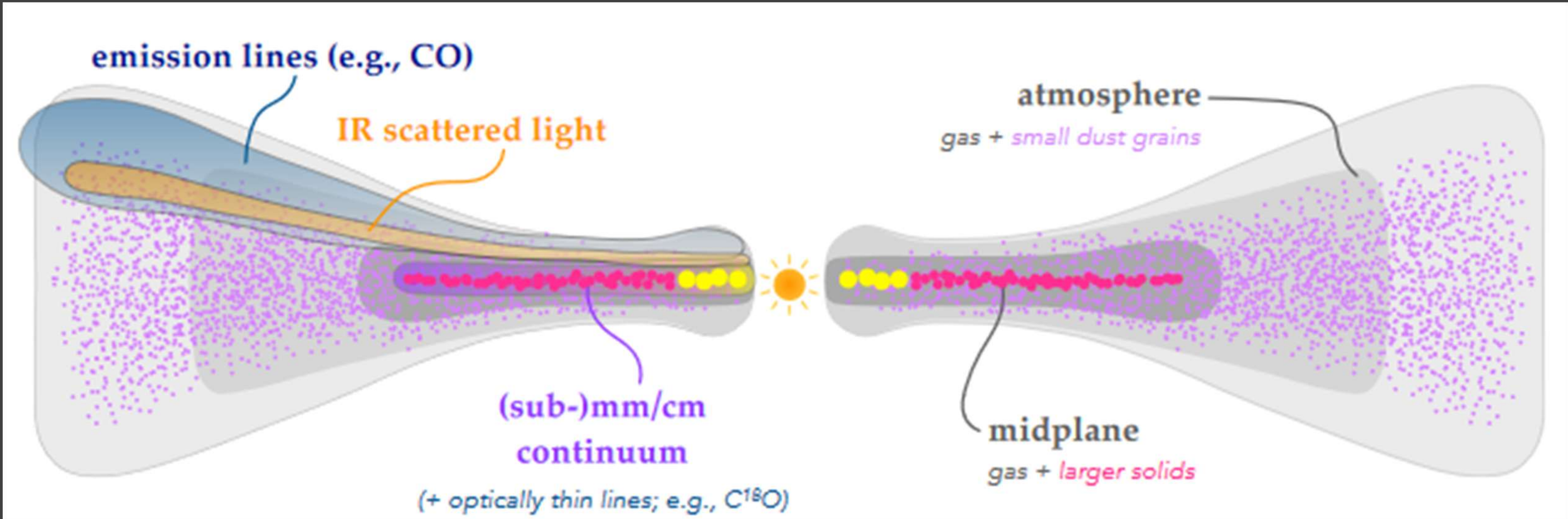


Elias 2-24



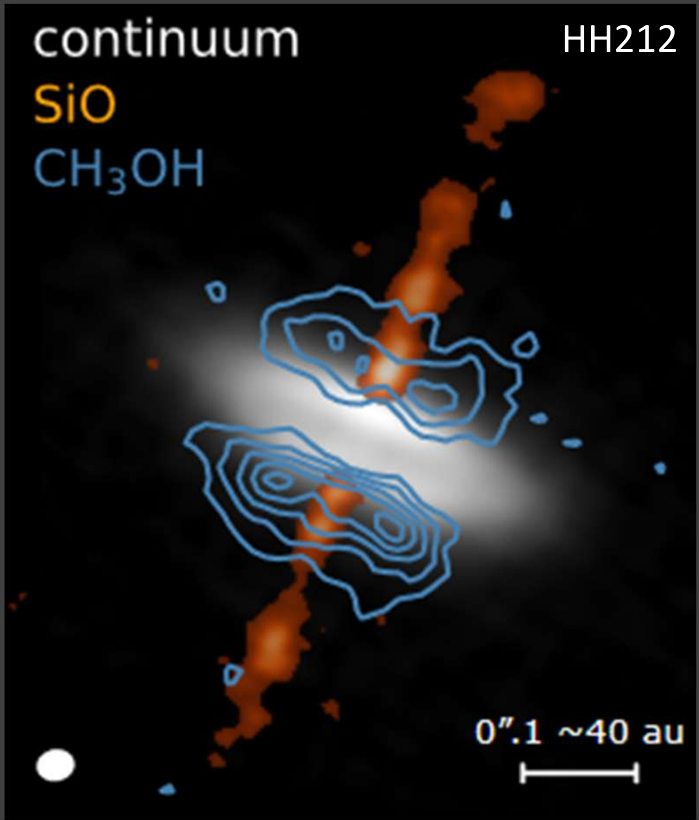
ALMA observations. 12CO line. A giant planet (superjupiter).

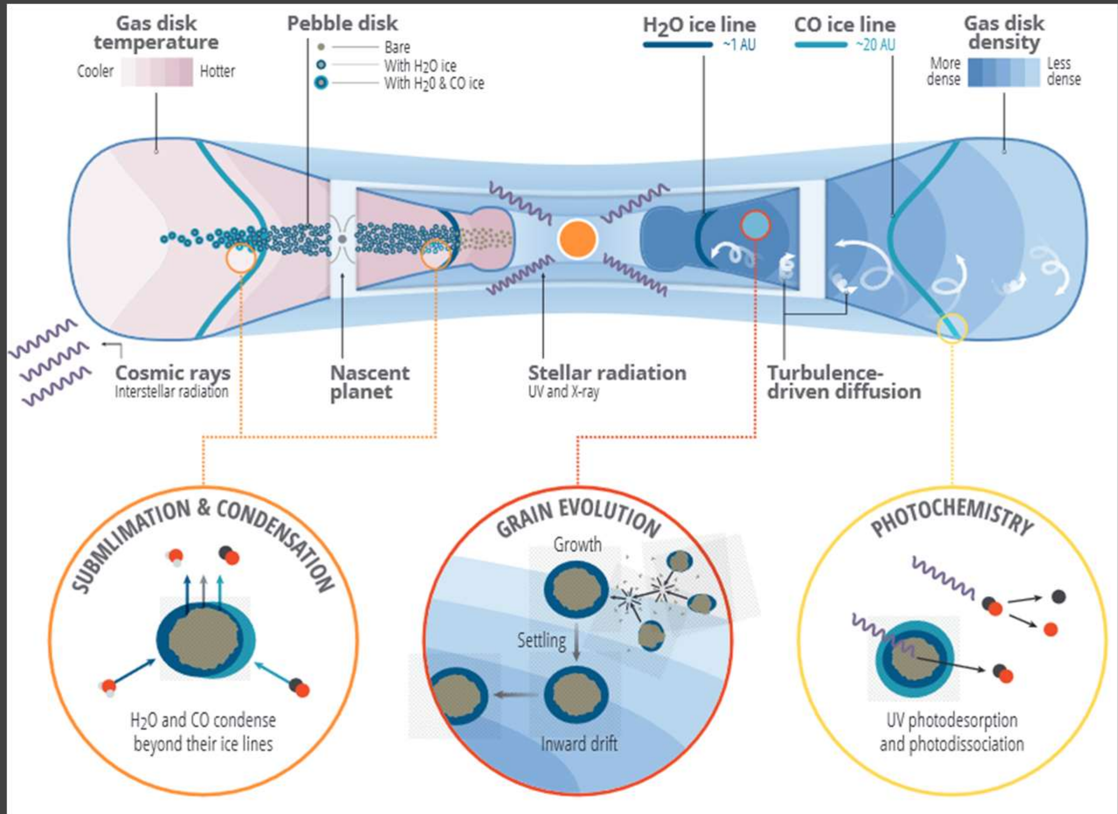
Disc structure and emission zones



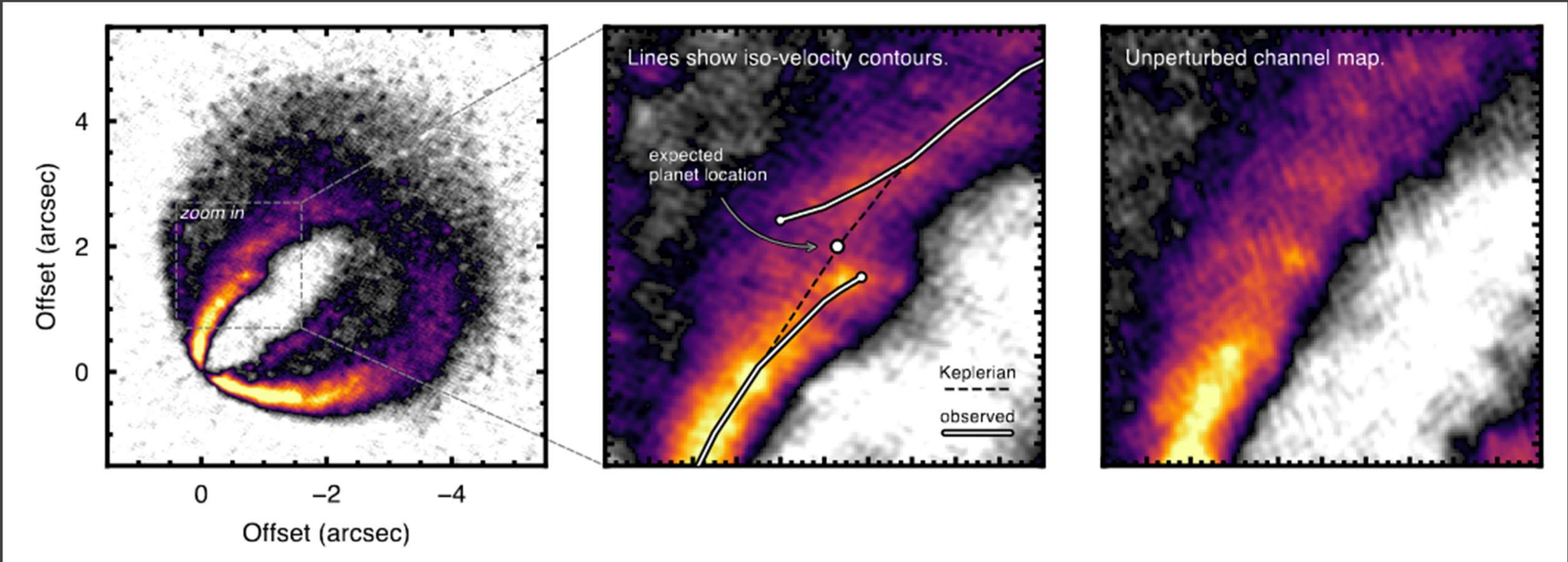
2001.05007

Structure and processes



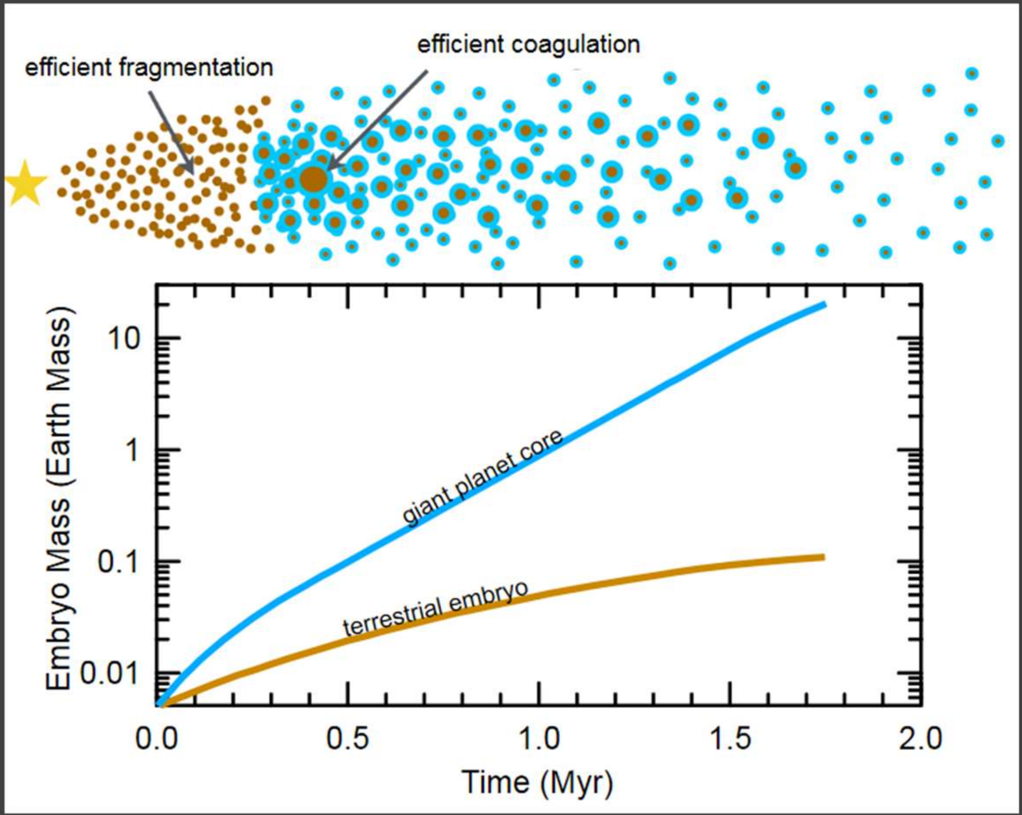


Planet and gas velocity in the disc HD 163296



2009.04345

Where planets grow?



To become giants, planets have to grow fast
as they also need to accrete gas
within the lifetime of the gaseous disc.

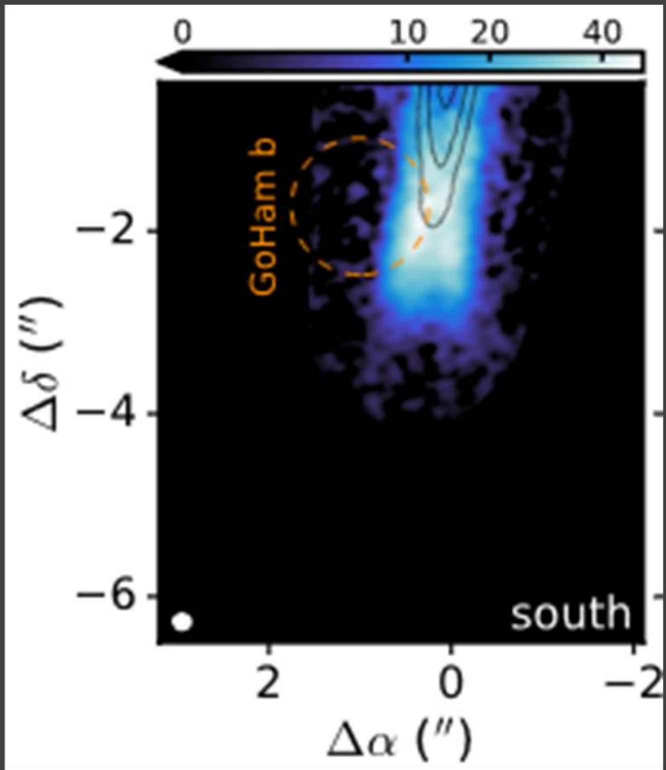
Fast growth is possible in the region of ice dust.

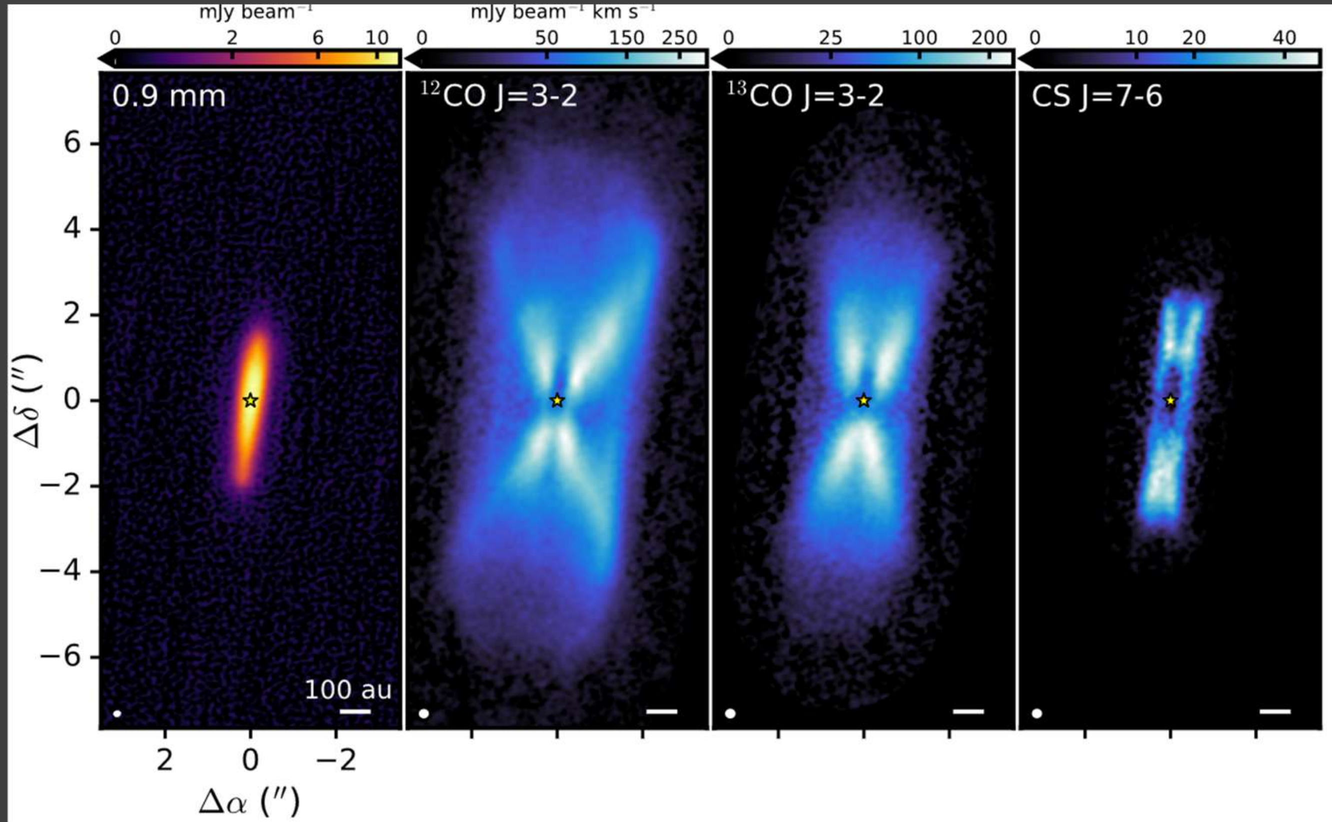
However, often we see giant planets
outside the region of ices.
This means – migration.

2010.03529

Early phases of a planet formation

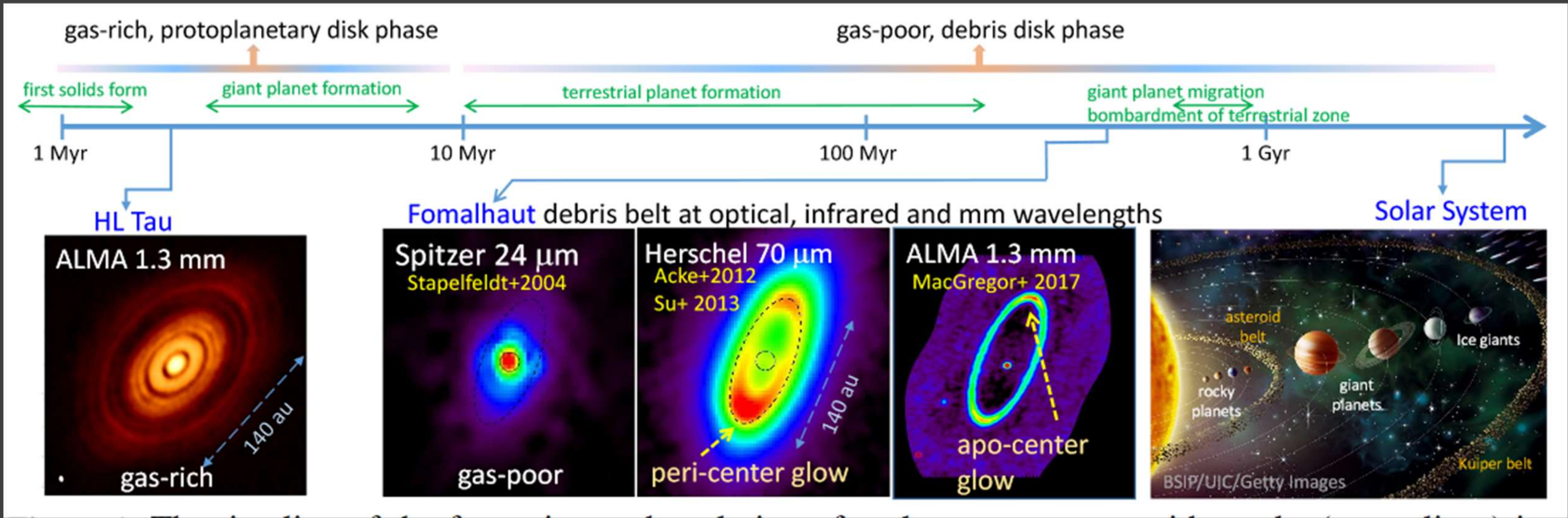
Gomez's Hamburger ('GoHam'; IRAS 18059-3211)



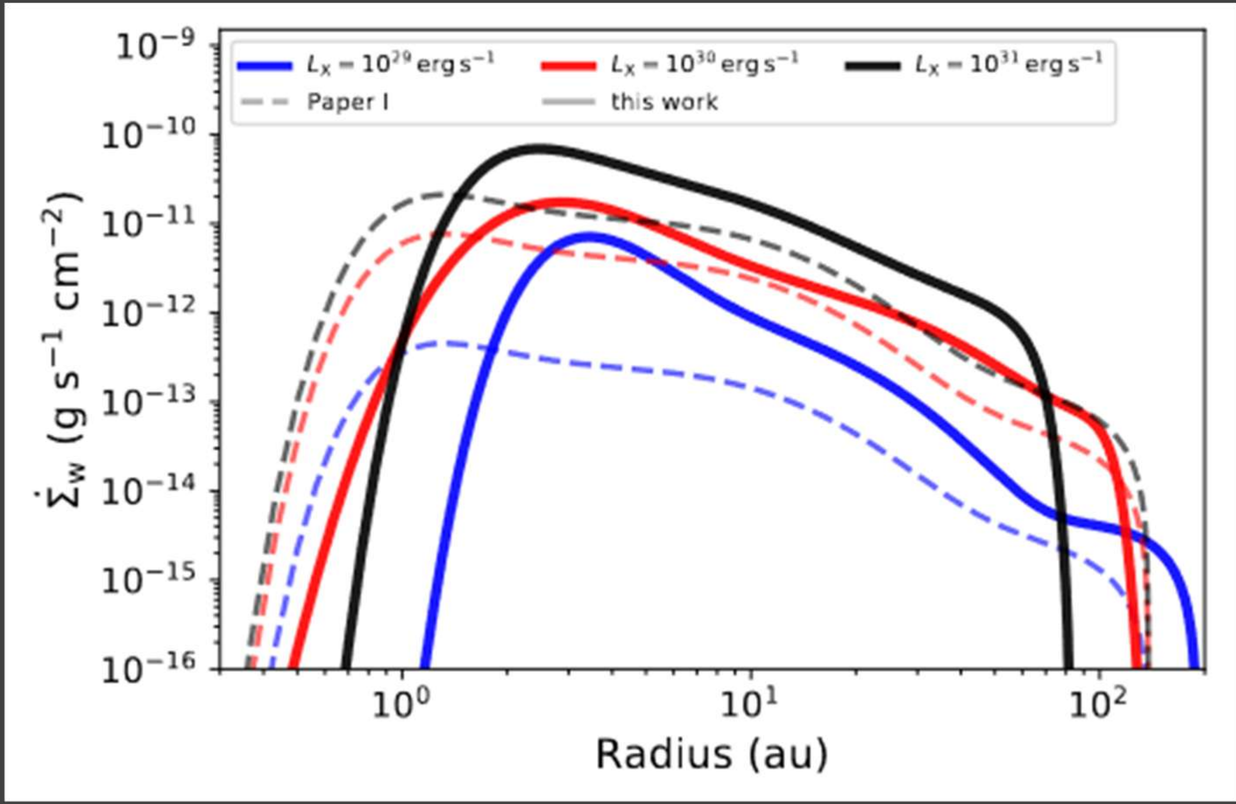


2609.09290

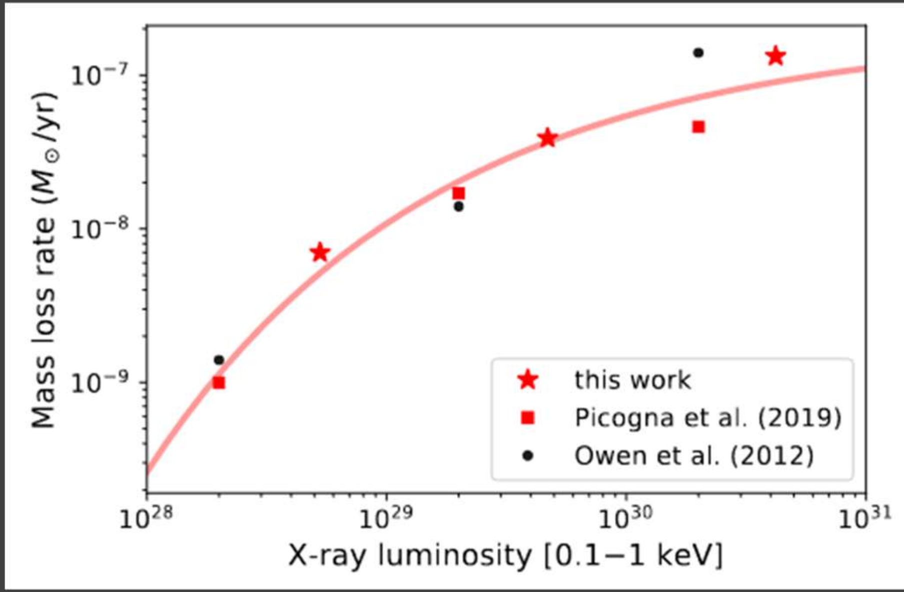
Protoplanetary and debris discs. Evolution



Photoevaporation



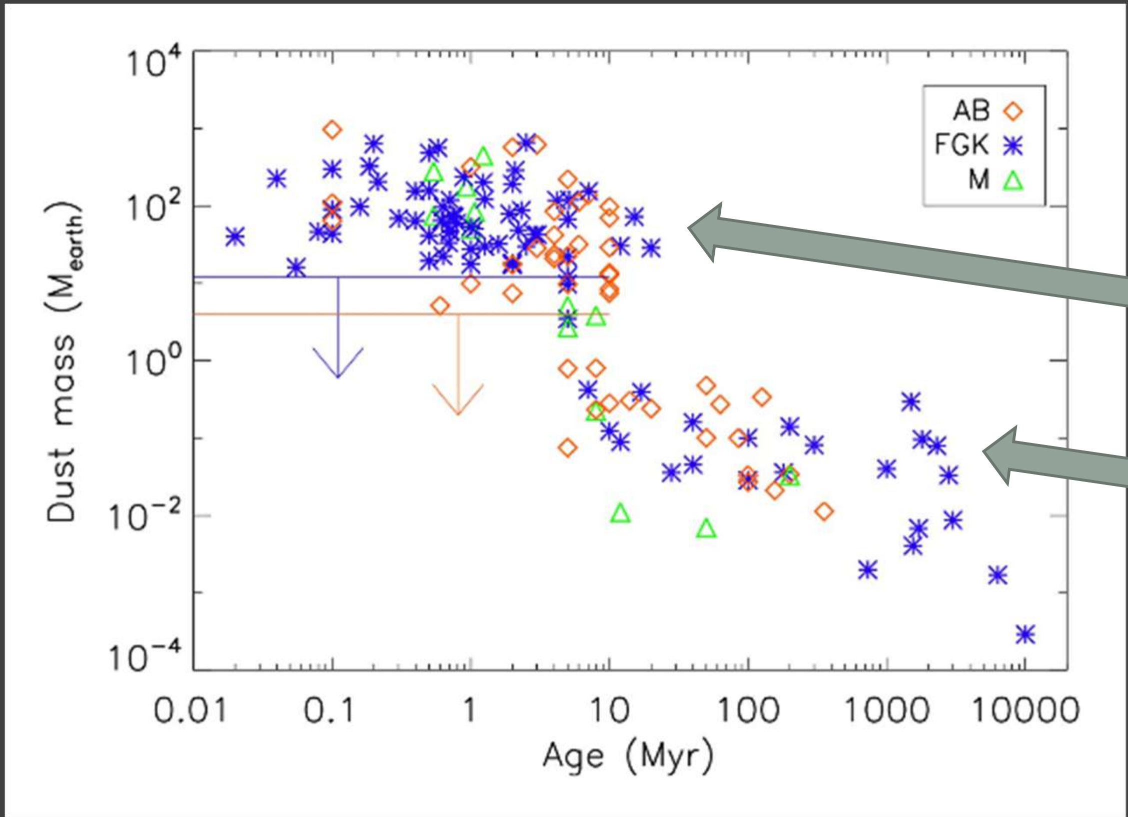
Gas is lost from the disc mainly due to X-ray and UV emission of the central star on the time scale ~few Myrs.



2109.04113

See also 1206.2367, 2112.00744 and then 2204.09704 for some recent discussion

Evolution of the dust mass in discs

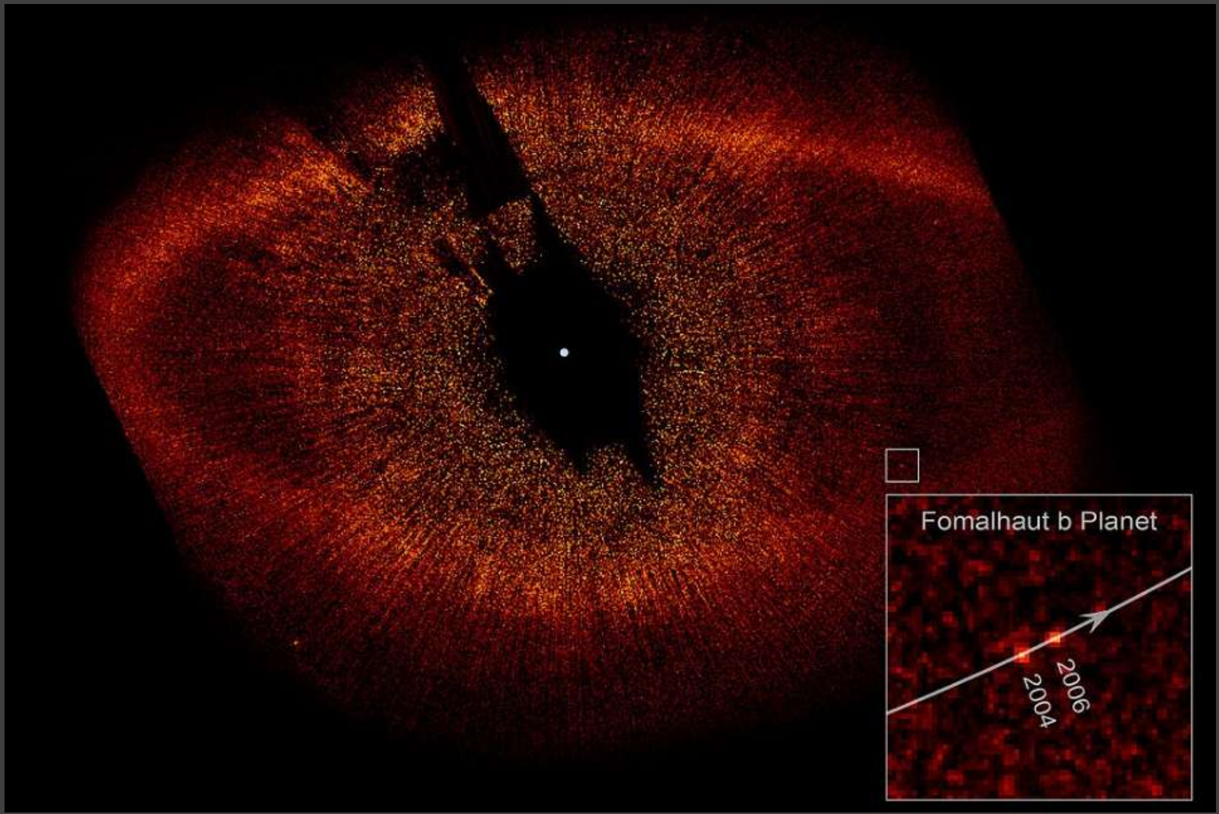


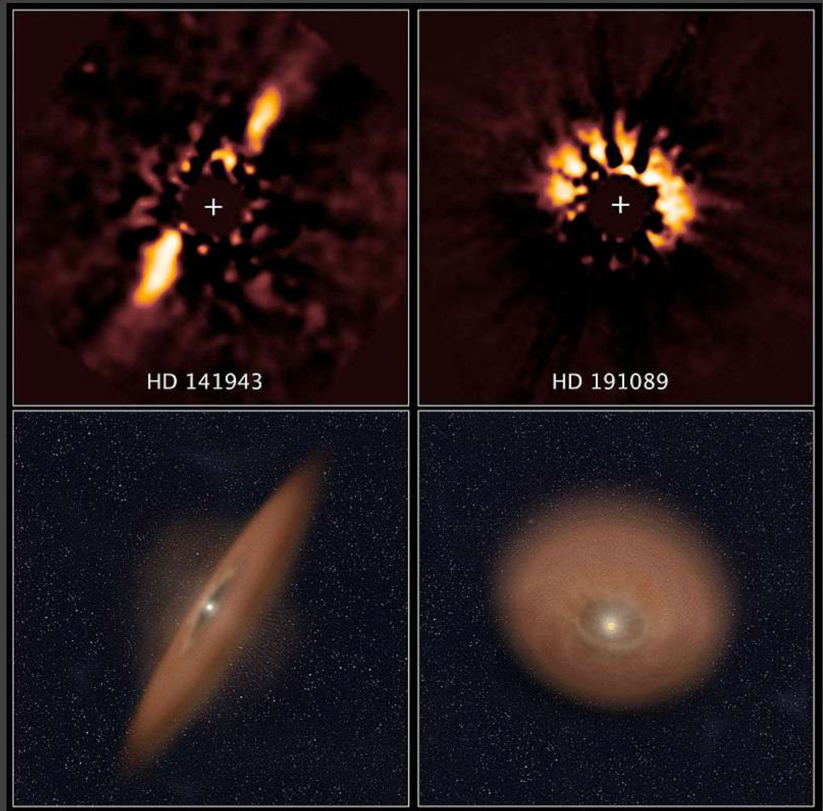
Protoplanetary discs

Debris discs

Panic et al. 2013, taken from the review 1703.08560

Debris discs





See a review in 2403.11804

~100 are imaged now 2110.04319; >1000 are known 2305.10364

Variety

Mainly, dust is observed.
Sometimes, gas or even planets are also seen.

The efficiency of emission at a given wavelength depends on the grain size.

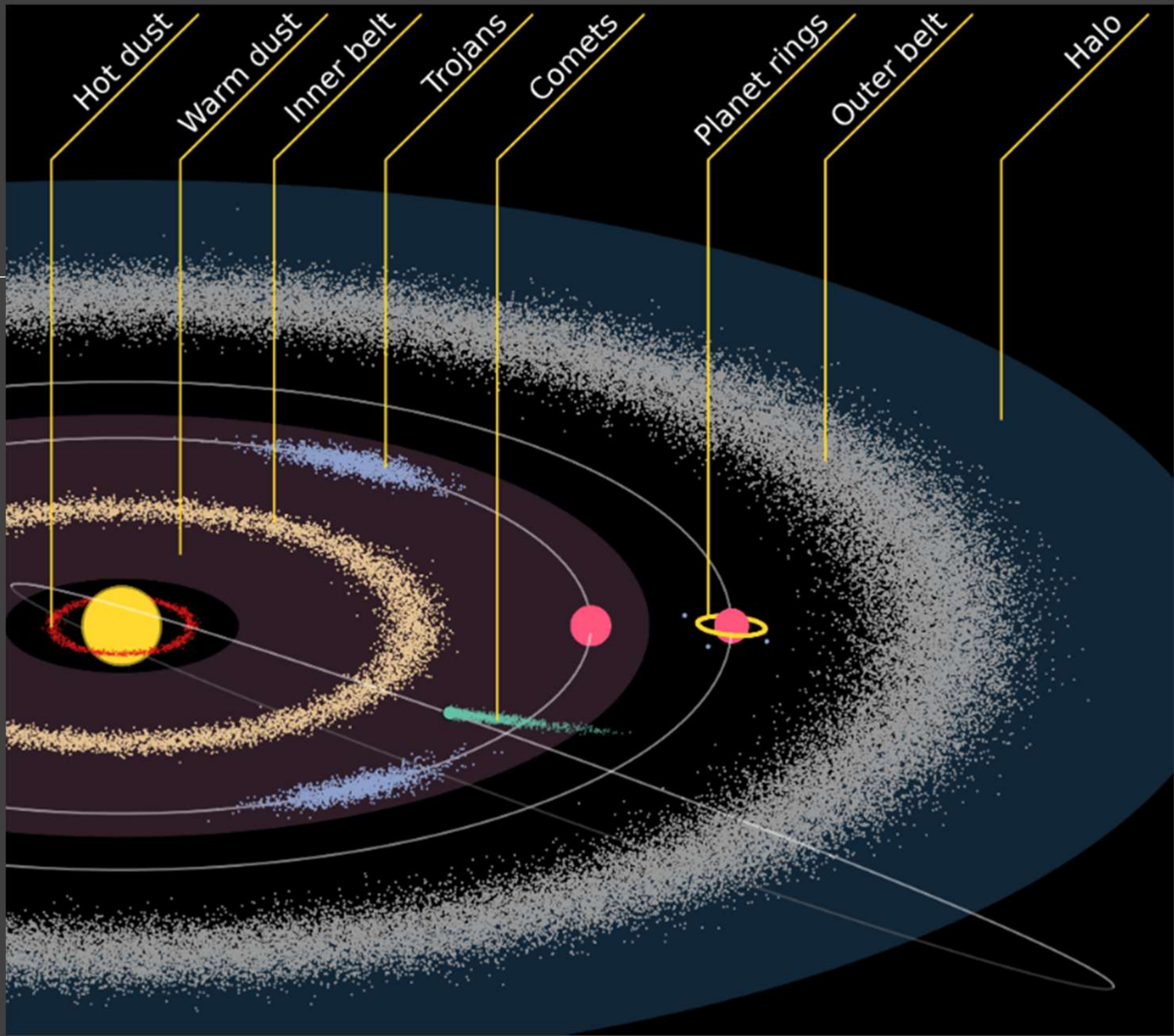
Debris discs are optically thin.

Debris discs lose mass over time.

Analysis of debris discs' properties can uncover the existence of planets in the system.

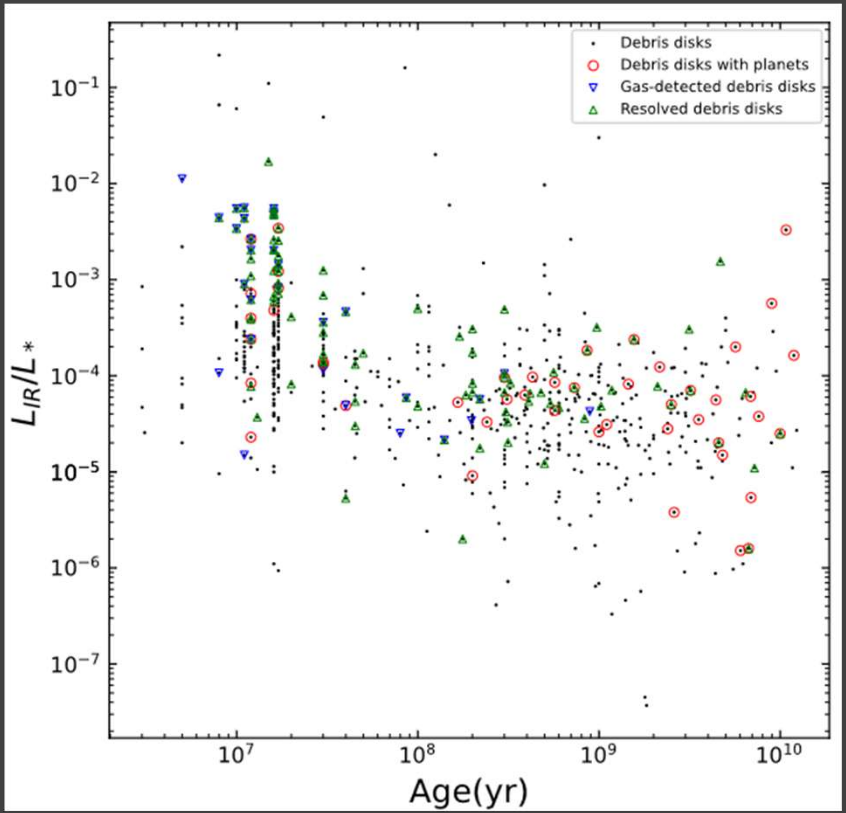
$$r_{\mathrm{BB}} = 1\ \mathrm{au}\left(\frac{T_{\mathrm{BB}}}{278\ \mathrm{K}}\right)^{-2}\left(\frac{L_*}{\mathrm{L}_\odot}\right)^{1/2}$$

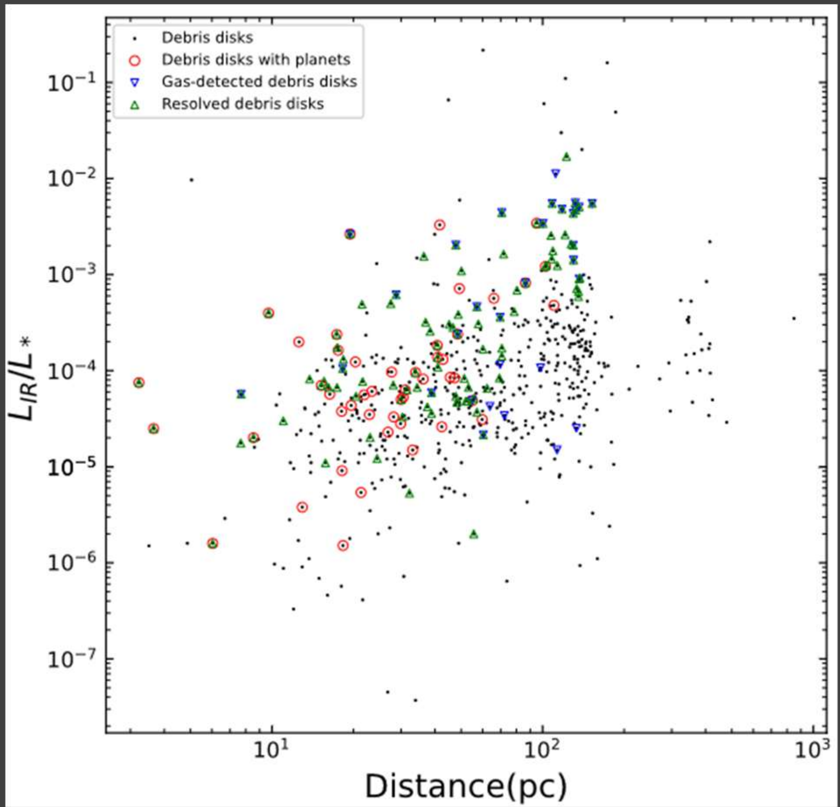
$$r_{\mathrm{d}} = \Gamma r_{\mathrm{BB}}$$



2403.11804

Statistics of debris discs





>1000 discs
>600 – golden sample

Stars from M to B

~50 discs with planets

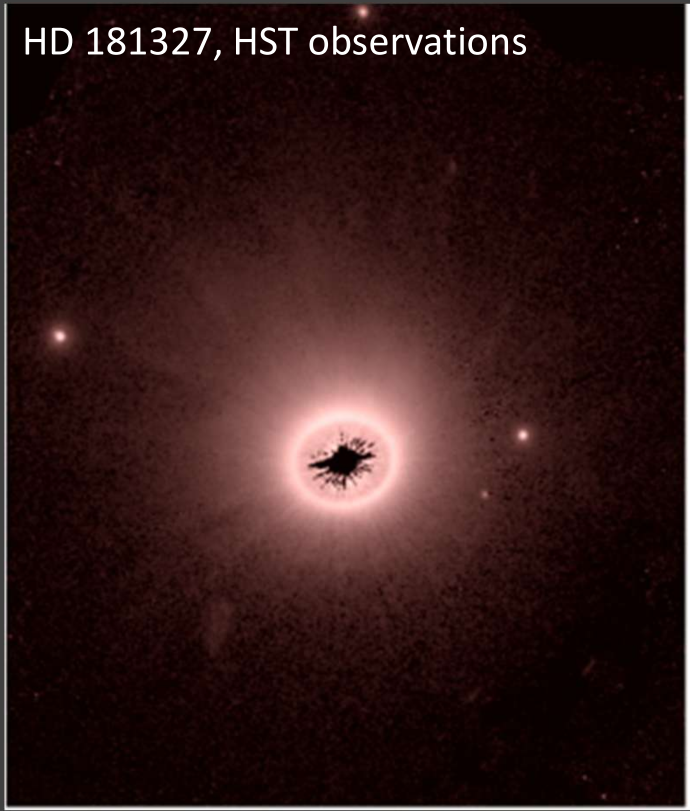
>30 discs with gas

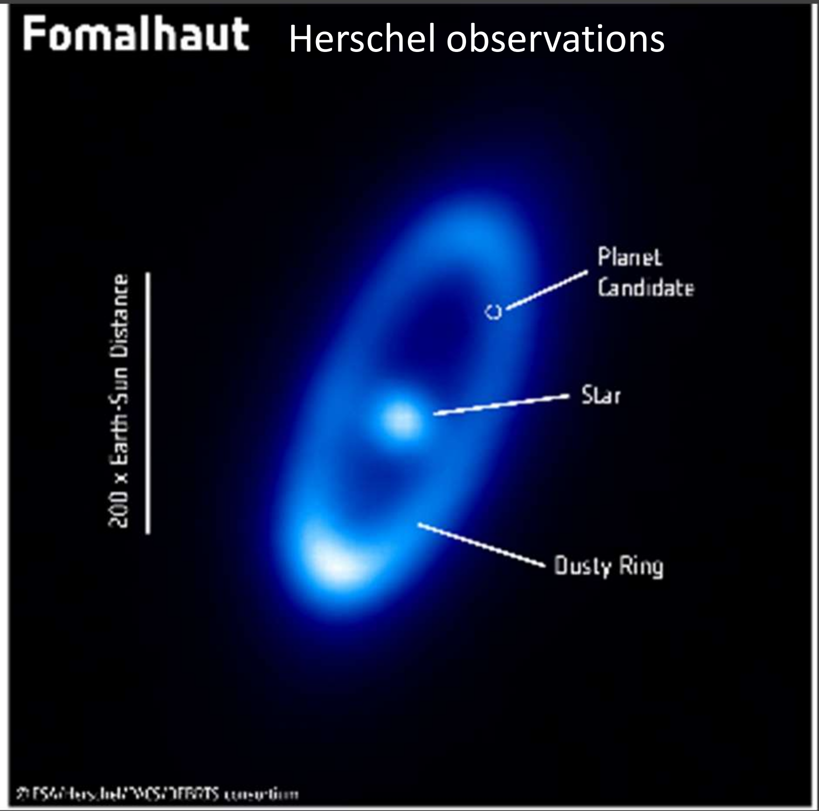
~100 resolved

2305.10364

https://www.circumstellardisks.org/

Two debris disc examples

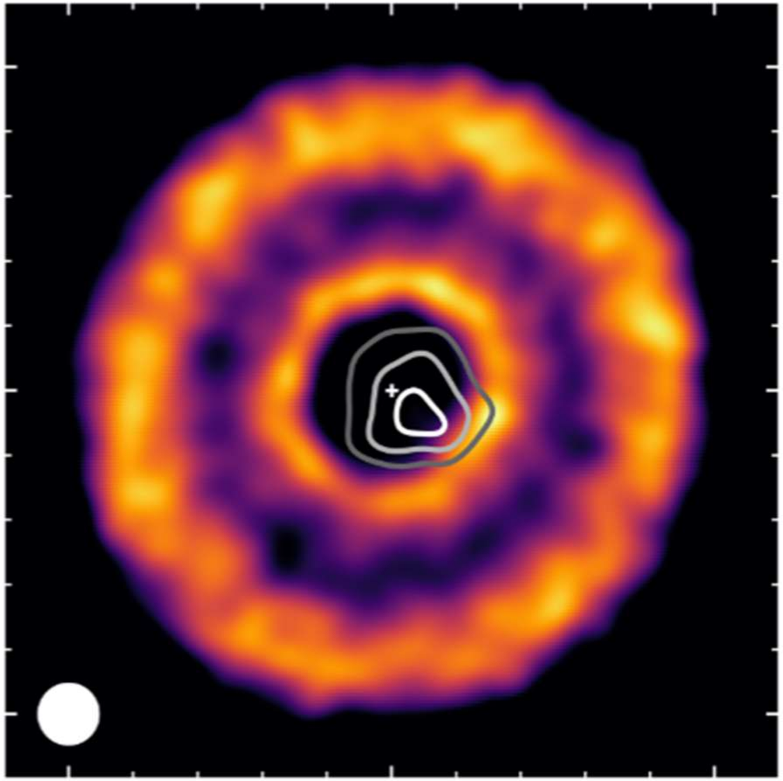


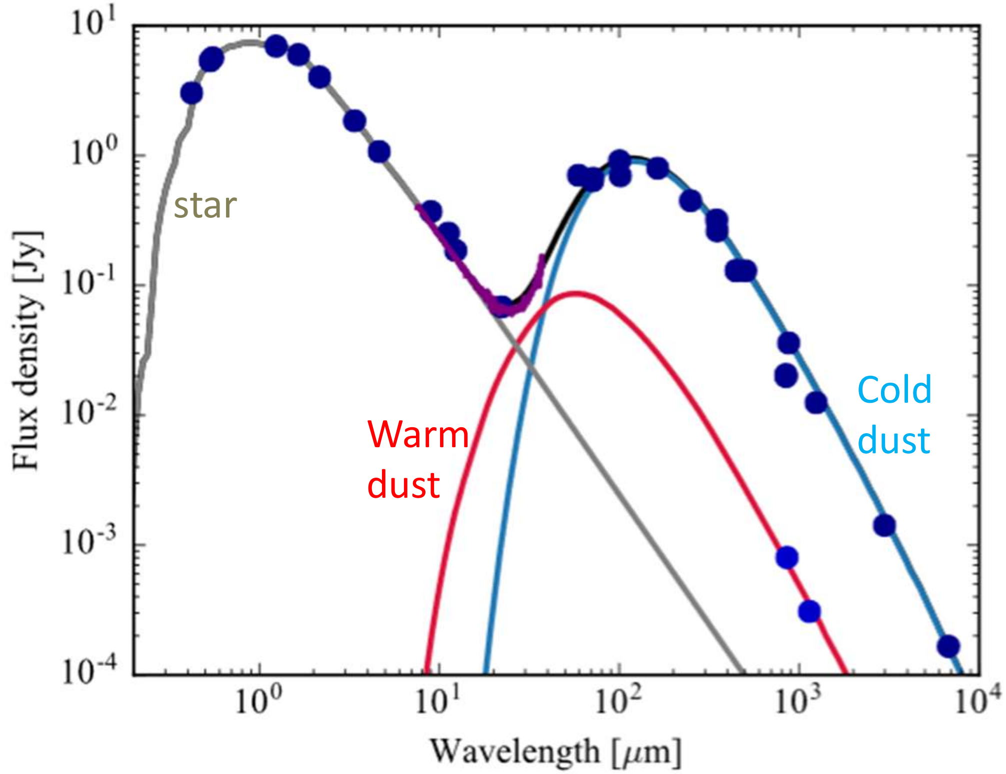


Hundreds of debris discs are known.

taken from the review 1703.08560

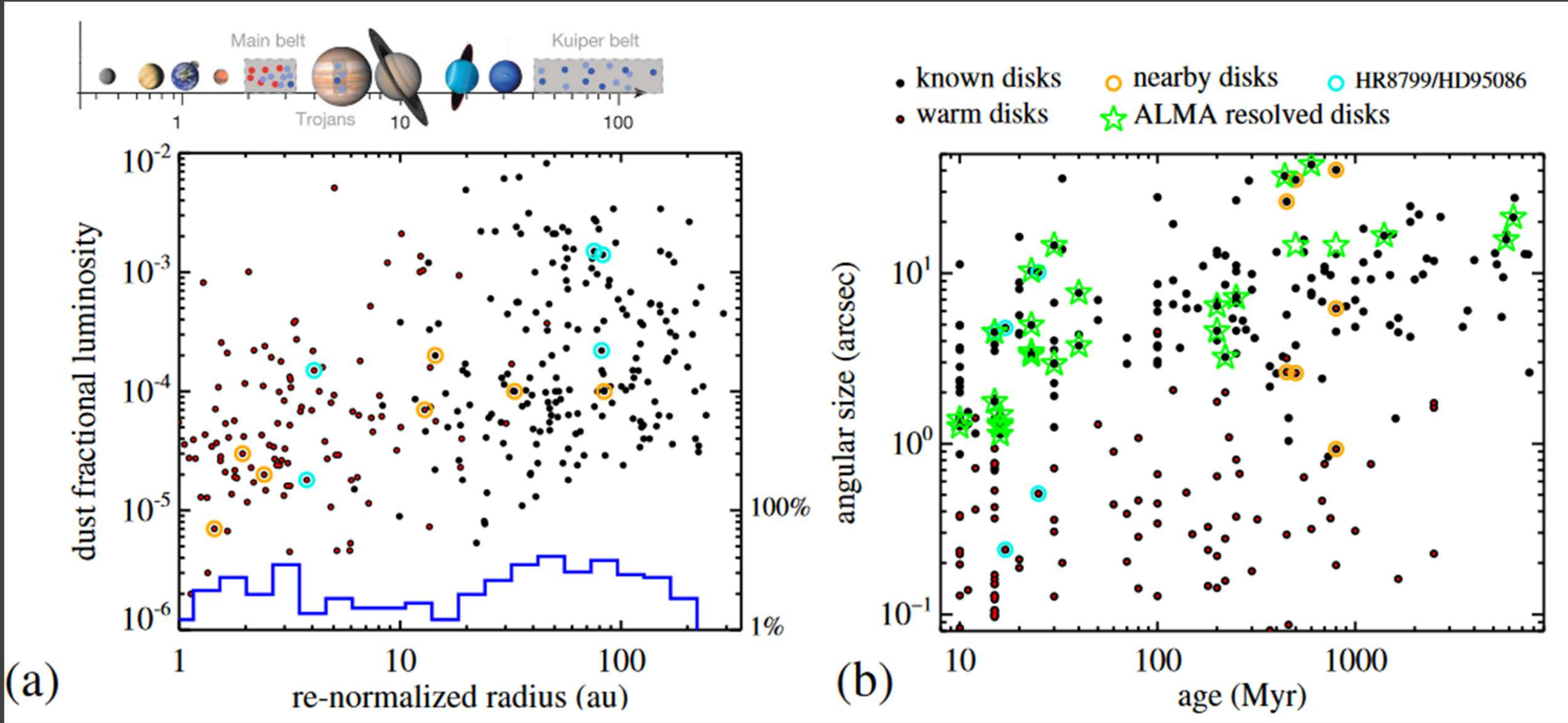
HD107146. ALMA observations





1804.08636

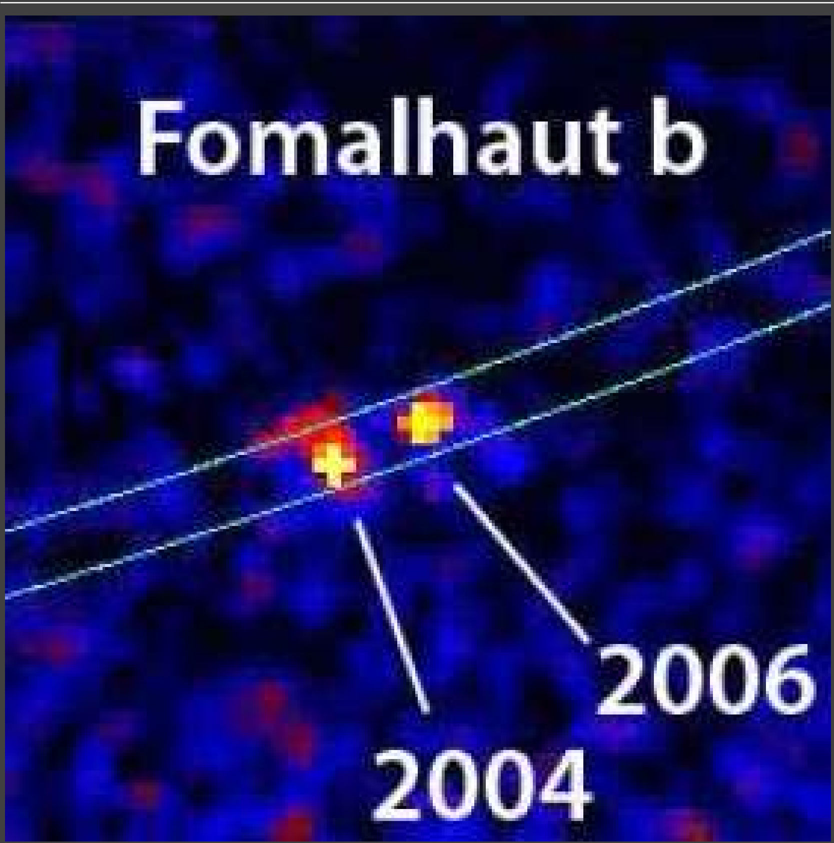
Debris disks are the dust disks found around ~20% of nearby main sequence stars in far-IR surveys.



Debris disc sizes are renormalized with luminosity $\sqrt{L_*}$ to co-align snow lines.

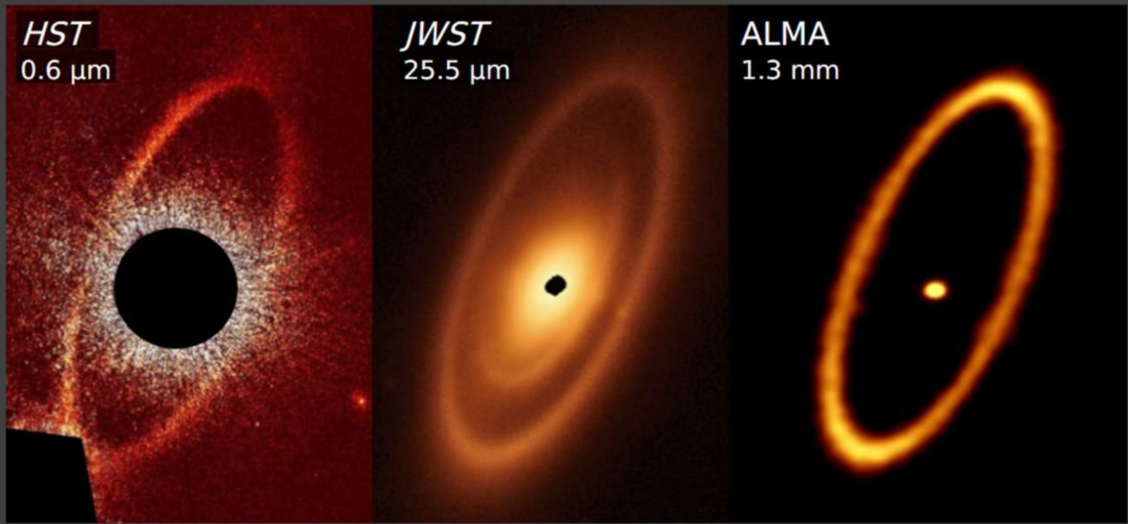
1903.10616

Fomalhaut b

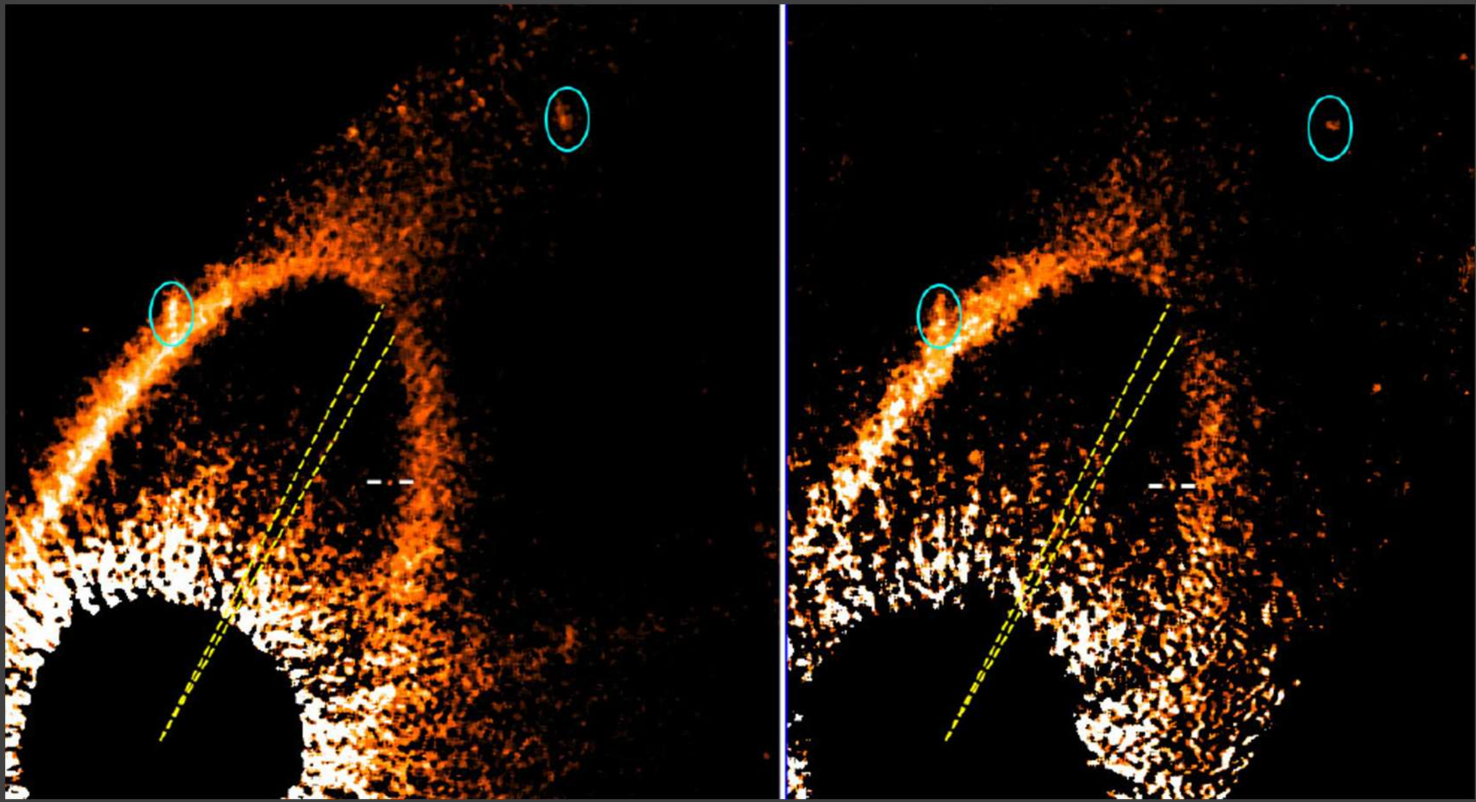


115 AU from the star

At first, it was considered a planet candidate.

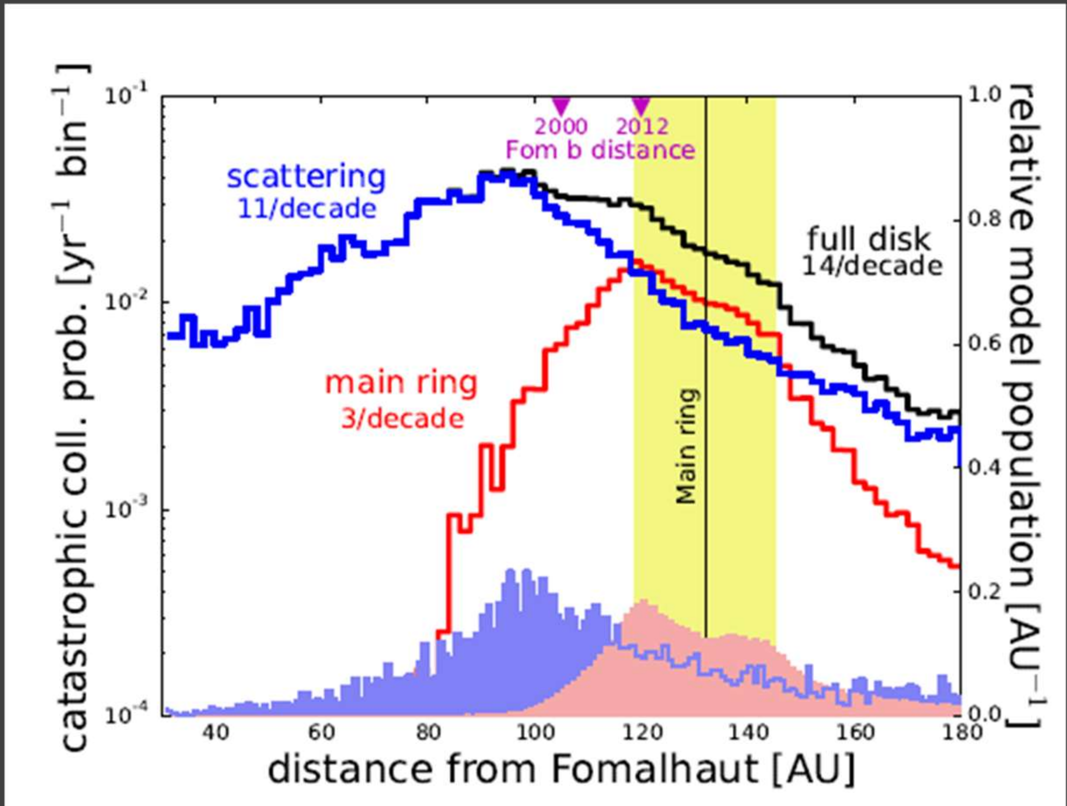


Is Fomalhaut b a real planet?



A planet or not a planet?
This is the question!

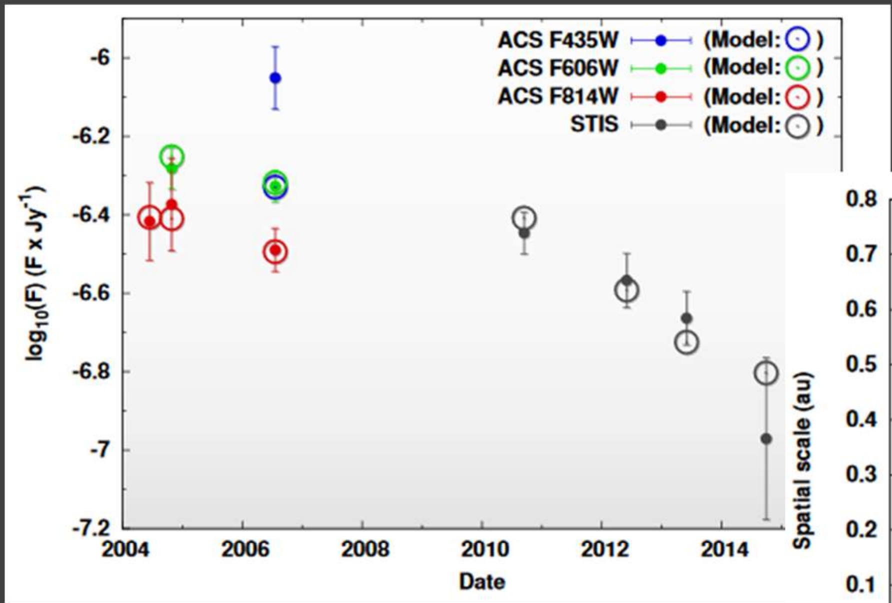
Result of a recent collision?

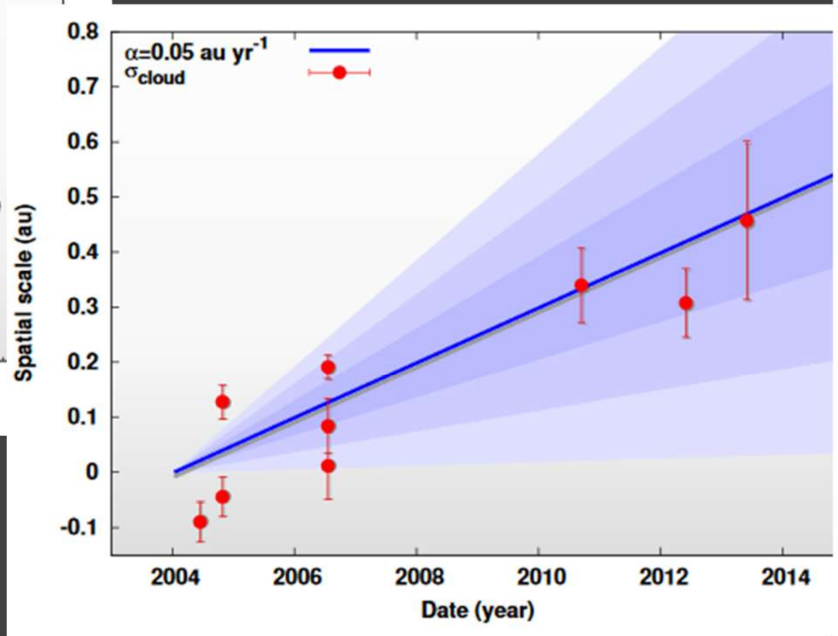


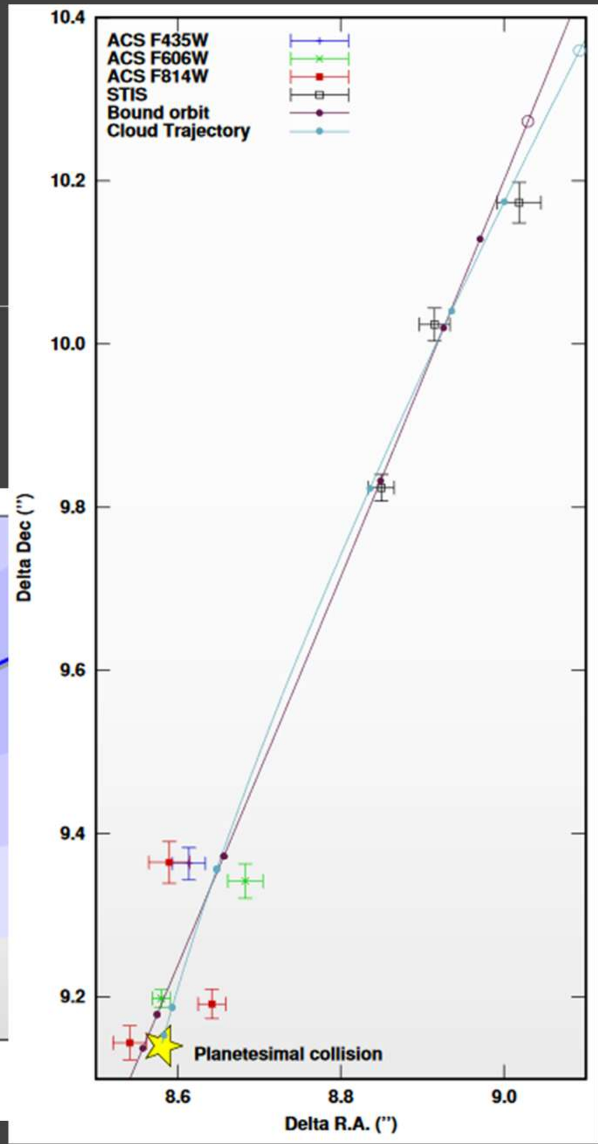
The object is situated in the region where collisions are very probable.

Two bodies with ~100 km size might be enough.

Collision is almost proved

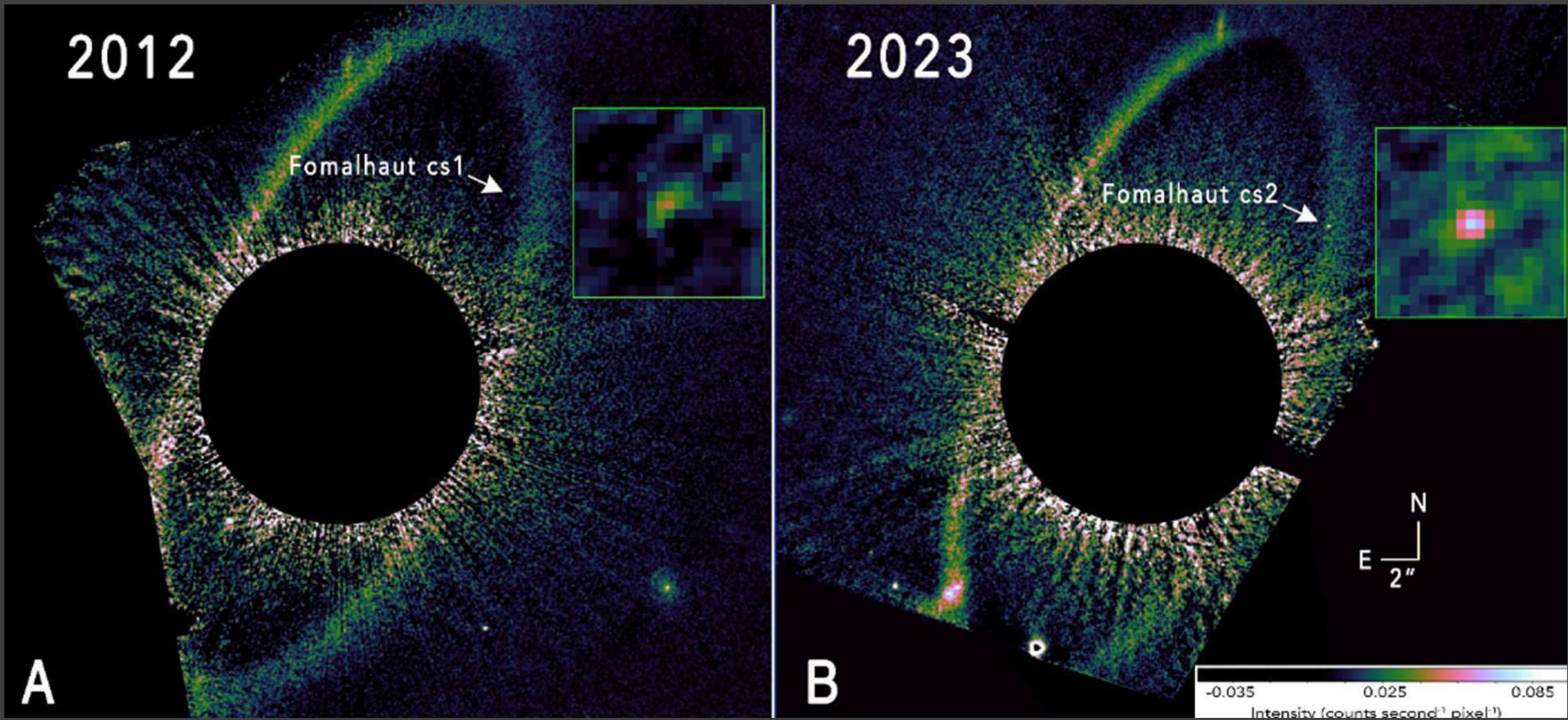




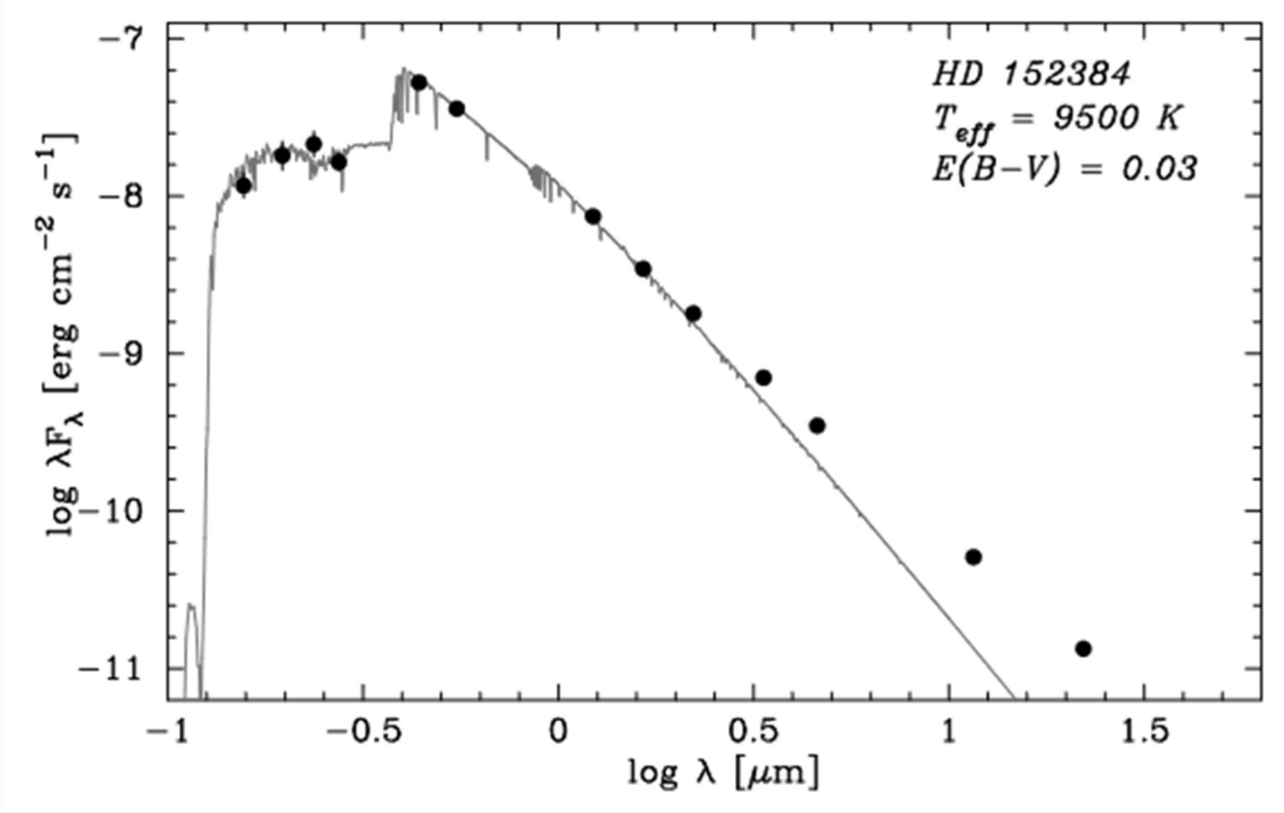


Oops, they did it again

The second collision in the Fomalhaut system



Collision around an A-star



Age 5-10 Myrs.
Wide binary (~10 000 AU).

VLT observations. XSHOOTER spectrograph.

Compact (<0.3 AU) debris-like disc
without volatile materials
(hydrogen, helium – only in absorption)
while Ca, Mg, Si, Fe are seen in emission.

May be a result of collision of rocky planets.

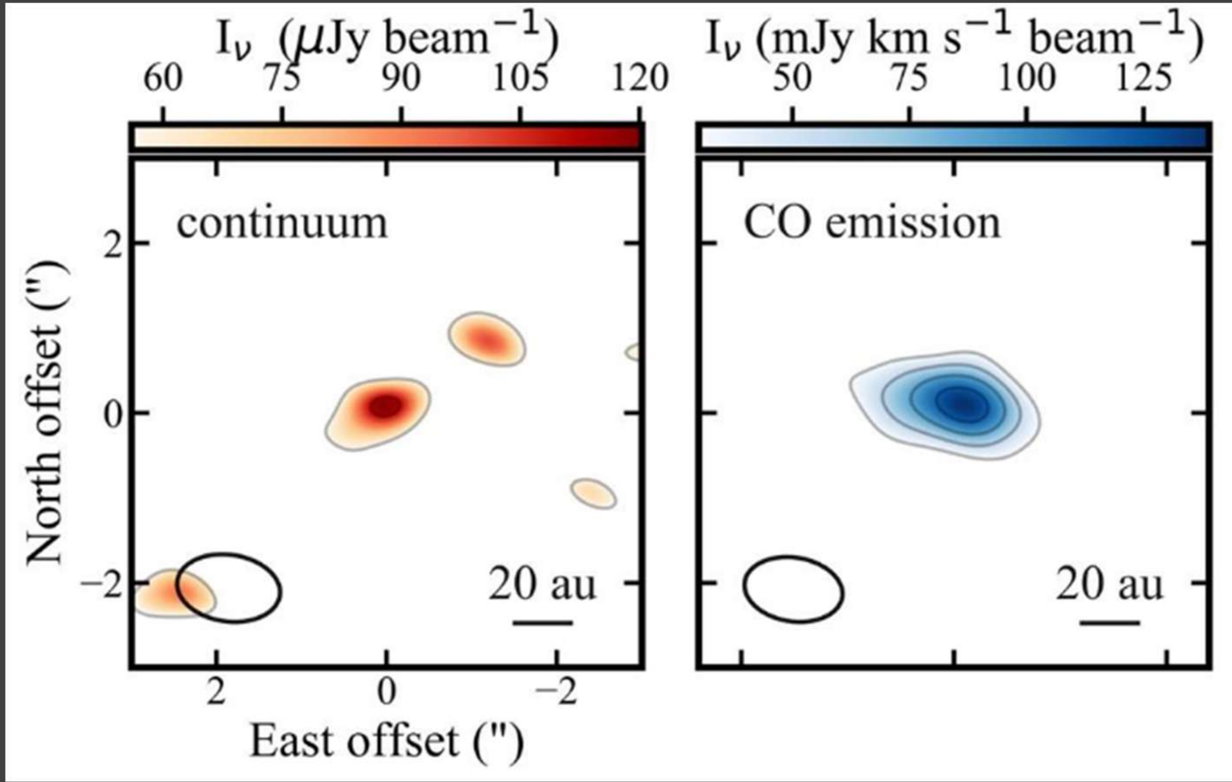
2105.08327

CO observations confirm a giant impact

HD 172555, age 23 Myr

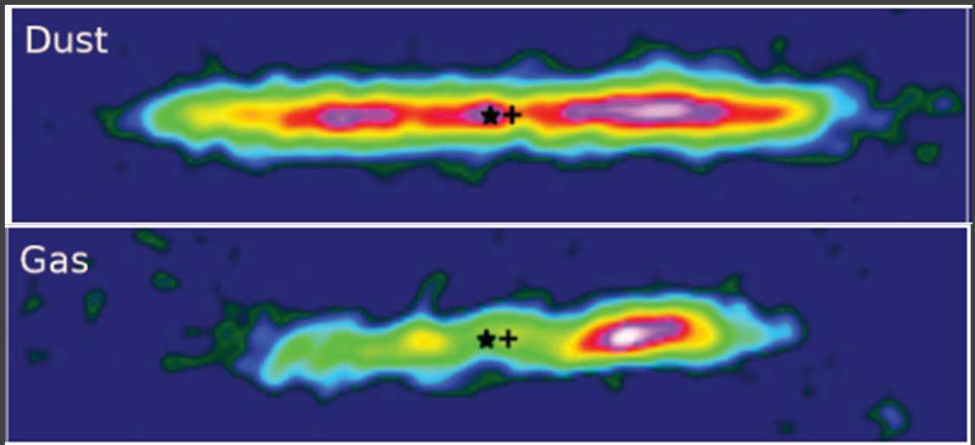
ALMA observations

CO is confined to a ring
of radius ~7.5 au and width ~3.3 au.

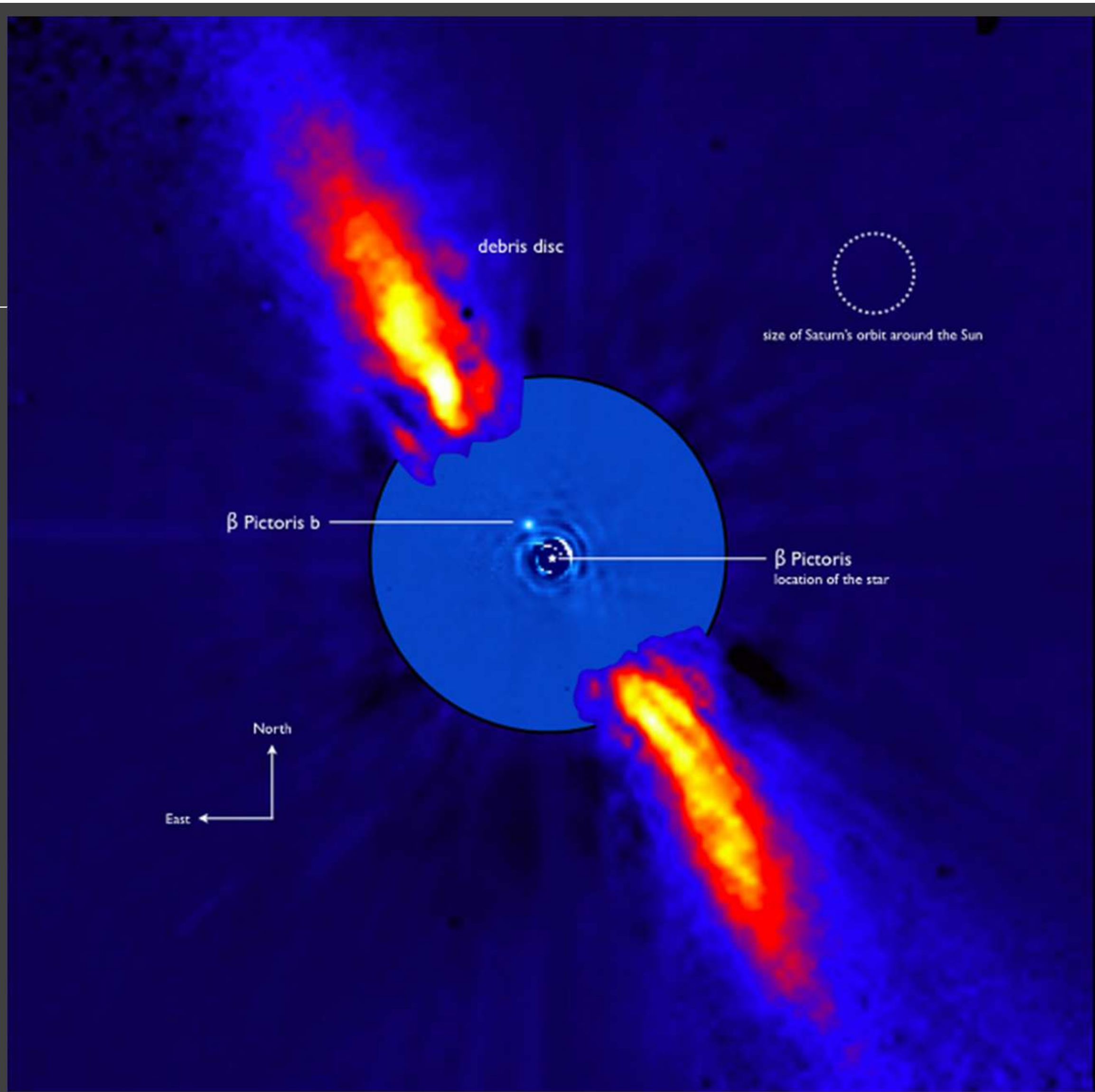


Beta Pictoris

Composite image obtained
by two instruments

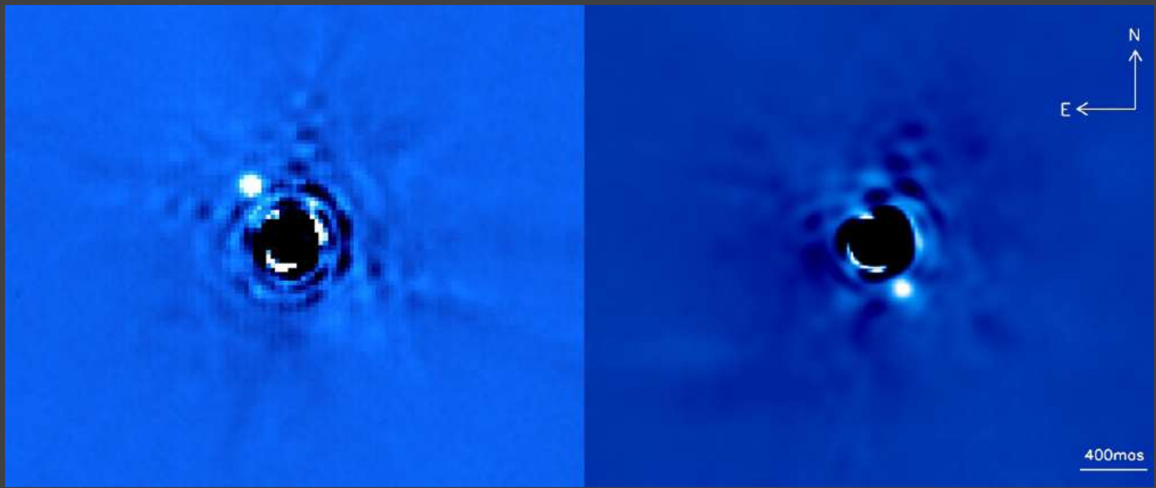


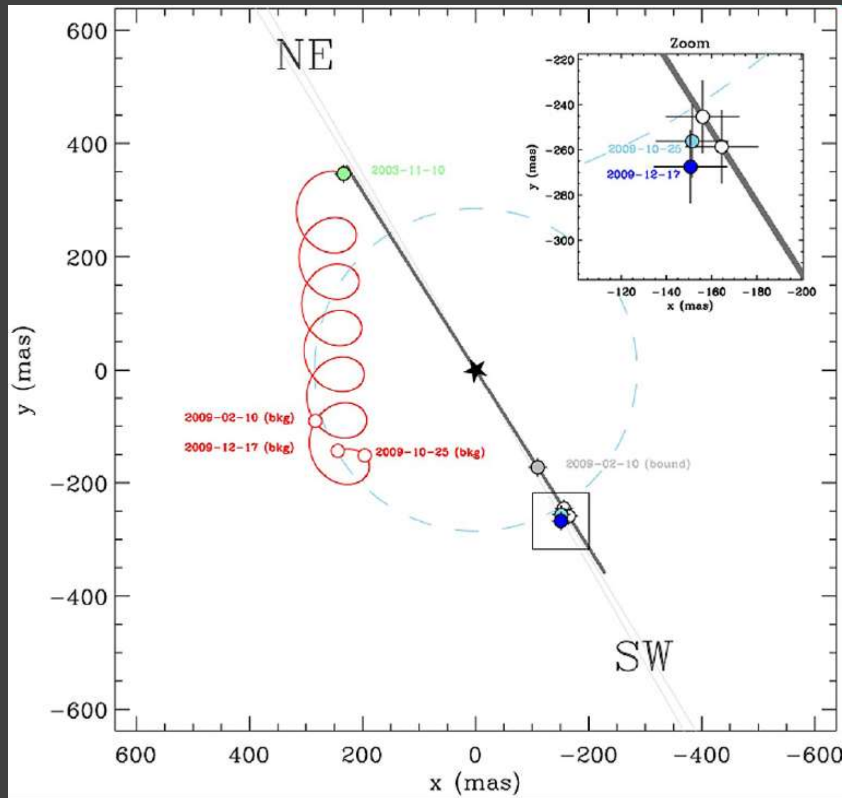
Gas is sometimes detected in debris discs.
CO emission detected by ALMA is shown above.
The sign "+" indicates the position of the planet.



taken from the review 1703.08560

Beta Pictoris





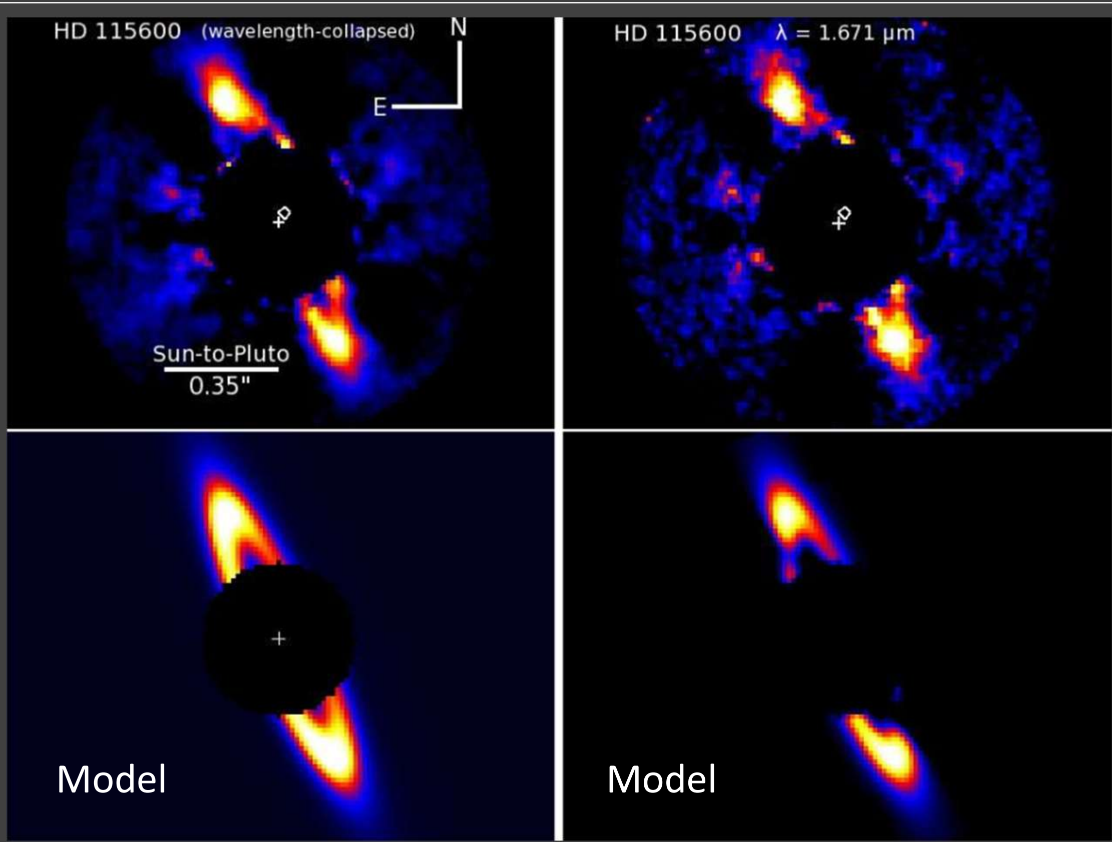
Age ~10 Myr
Distance ~ 9 AU

Young Kuiper belt-like debris disc

HD 115600
110 pc
15 Myrs
1.4 solar mass star

Gemini planet imager

Size of the disc 48 AU



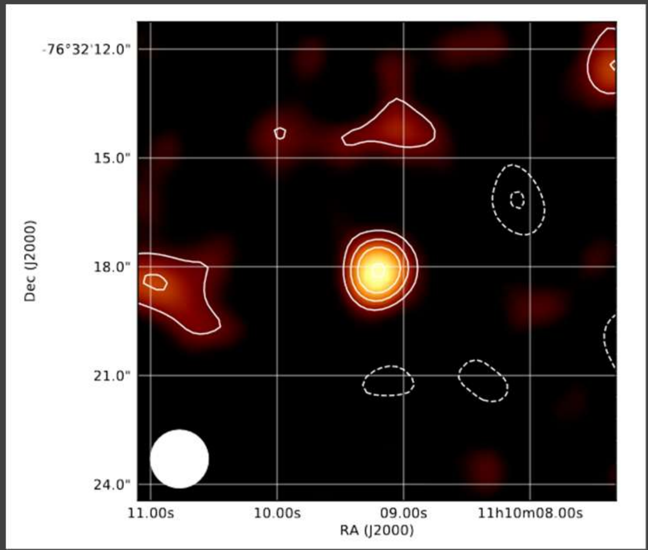
Disc around planetary mass object

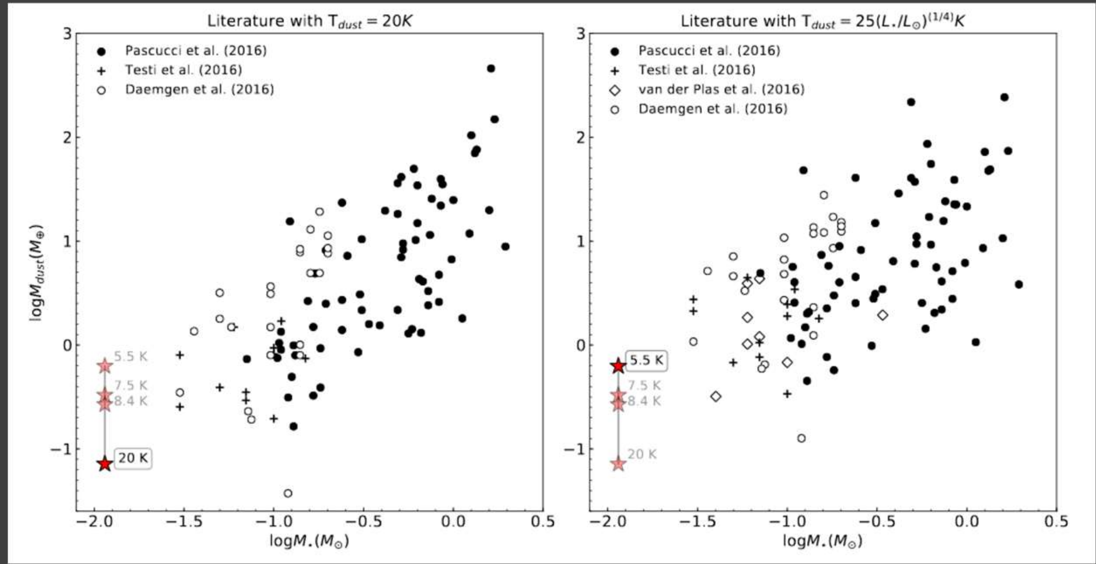
OTS44 is one of only a few free-floating planets known to have a disc.
Mass ~12 $M_{jupiter}$

IR excess seen by Spitzer and Herschel

ALMA observations

M_{dust} ~0.07-0.7 M_{Earth}



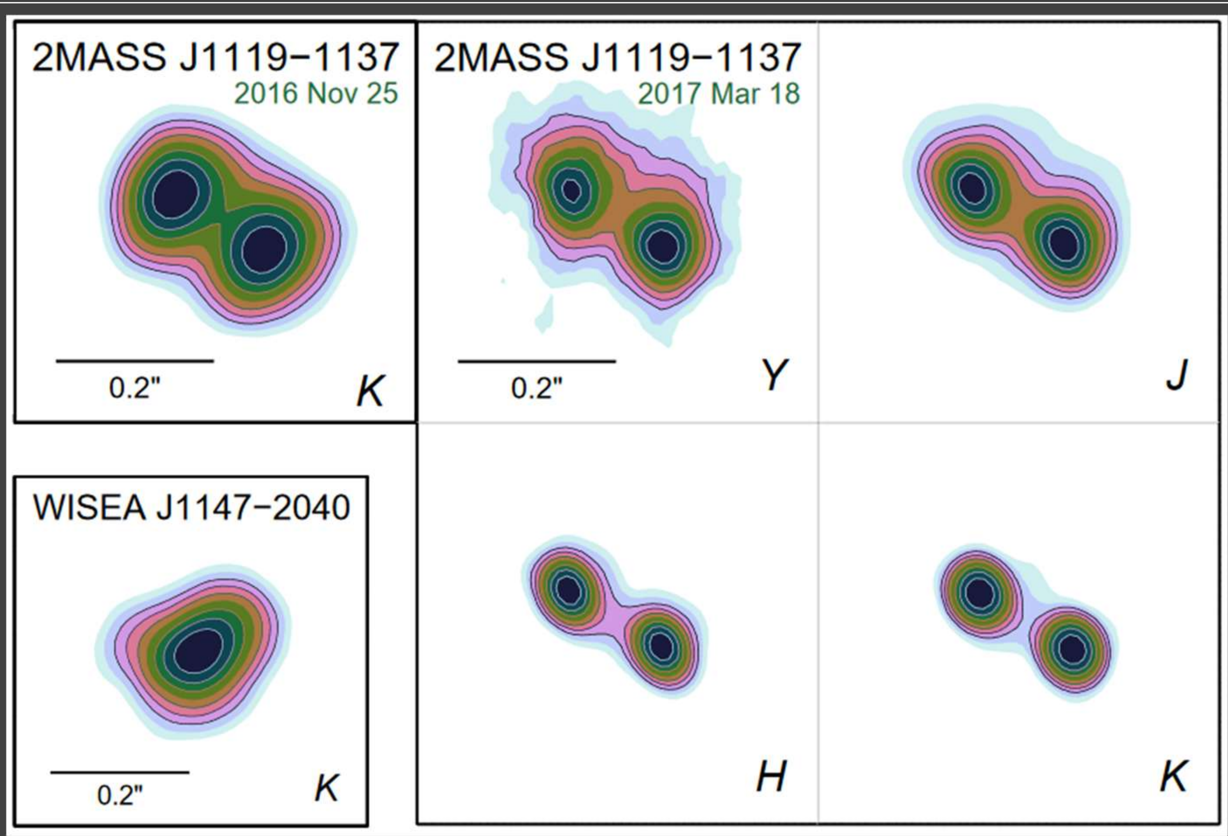


A brown dwarf is a pair of planets

2MASS J11193254−1137466

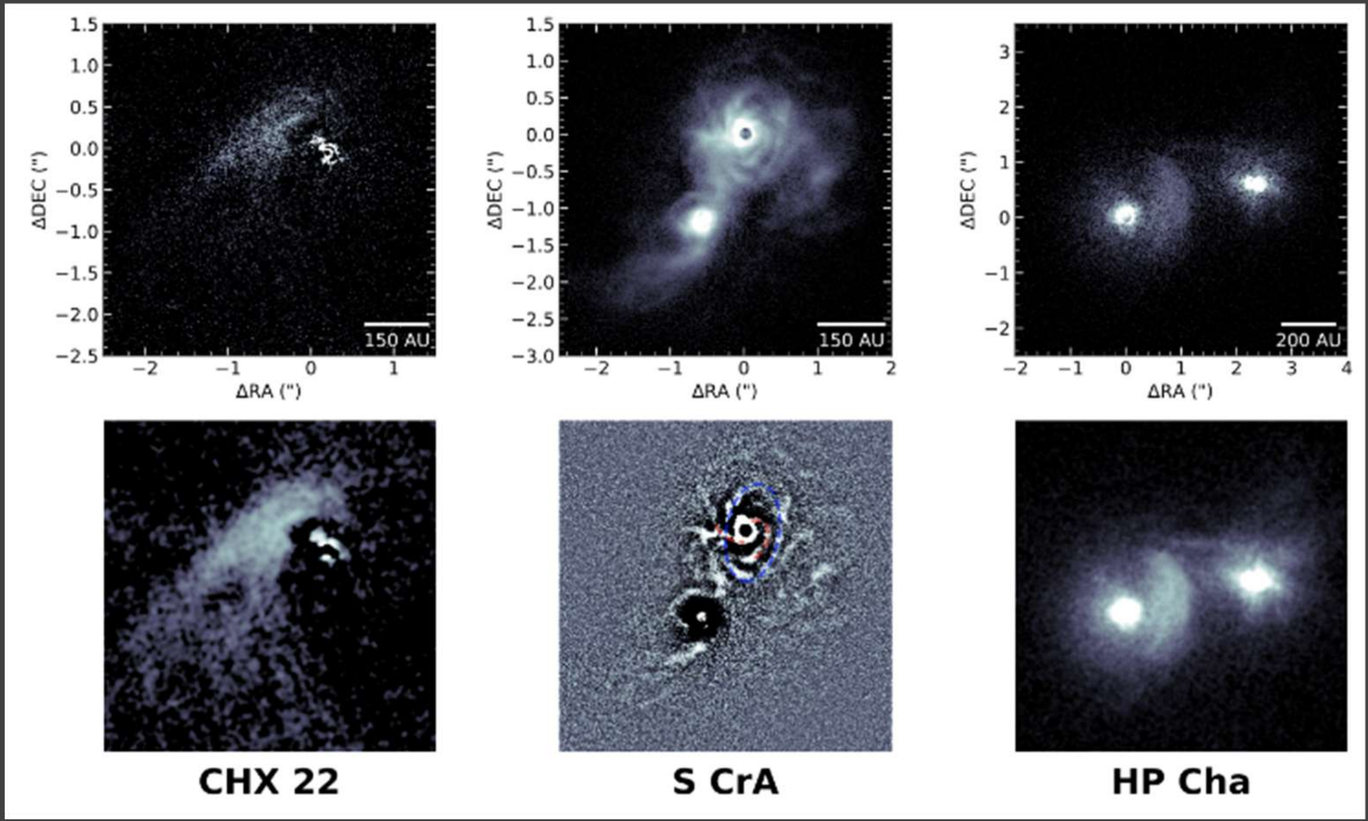
Age ~10 Myr
20-30 pc

M ~ 3-5 $M_{jupiter}$
Orbital period ~50-150 yrs
3-5 AU



1706.01883

Forming binaries with discs



Images obtained by SPHERE in polarized light.

On the left, we see a long tail.

In the center and on the right, we see well-developed discs around each component.
The system on the right is triple.

In the first case, the separation between stars is 46 AU.
In the second, 322 AU.
And in the third, the separation between the primary and a tighter binary is ~500 AU.

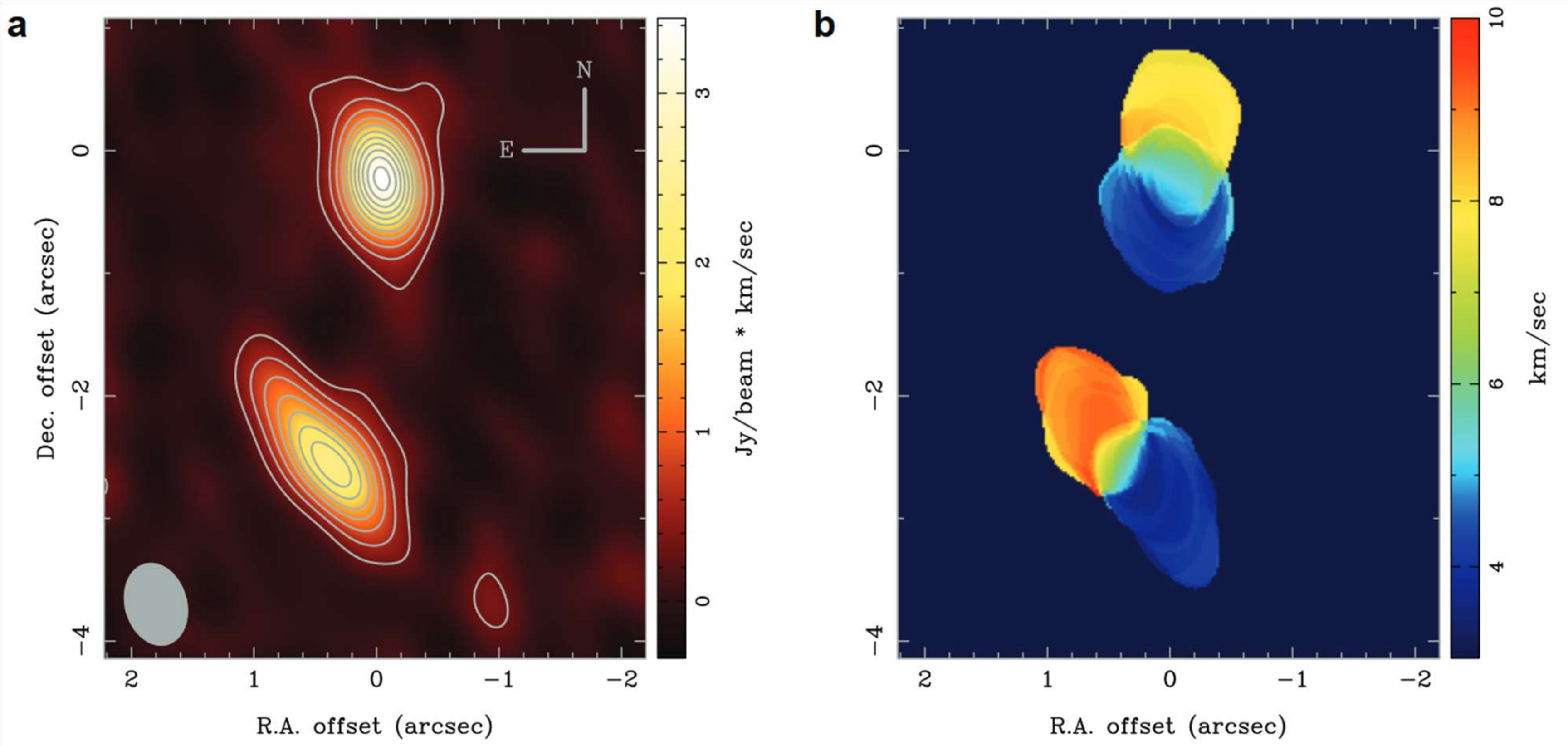
Protoplanetary discs in a binary system

HK Tau
161 pc

1-4 Myr

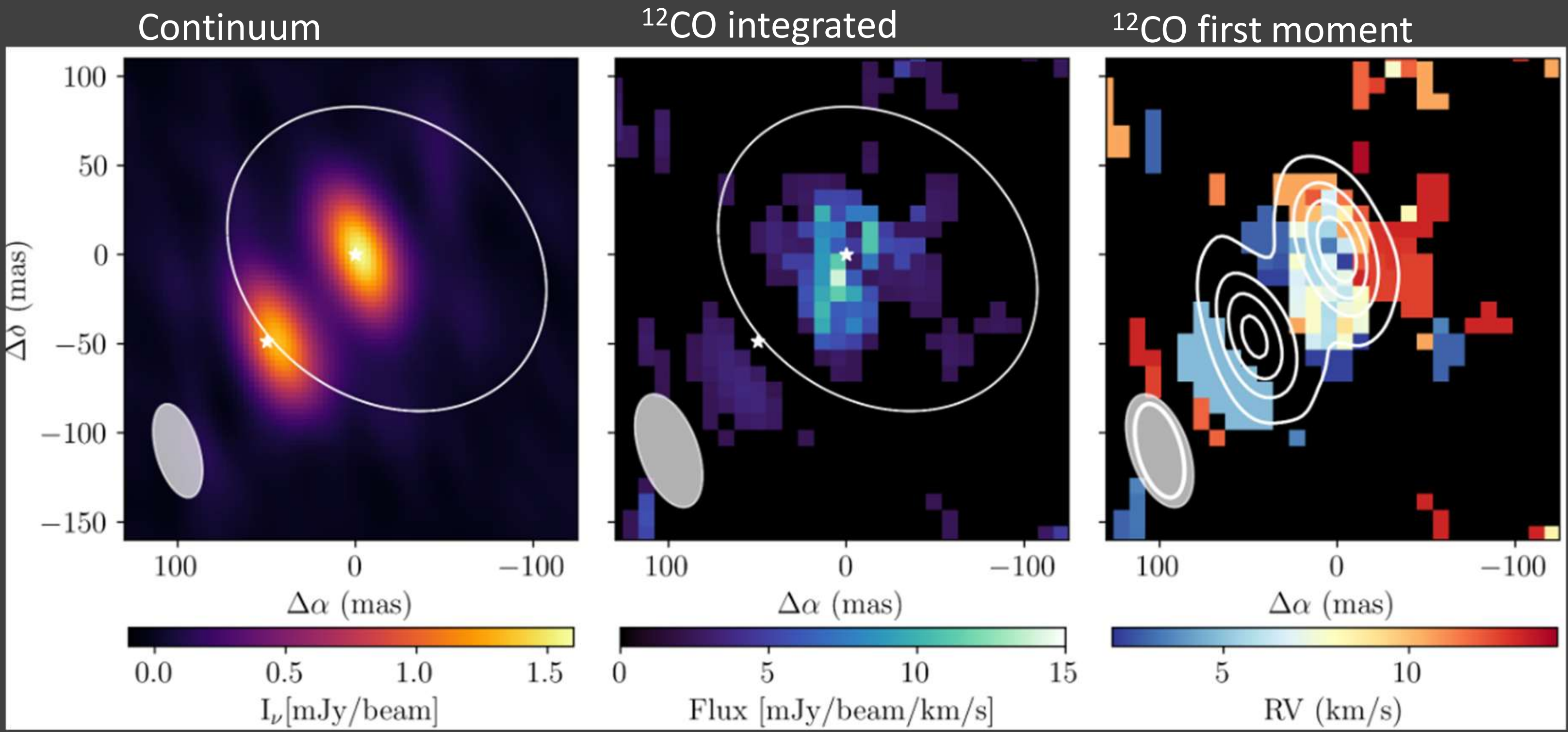
386 AU binary

ALMA observations



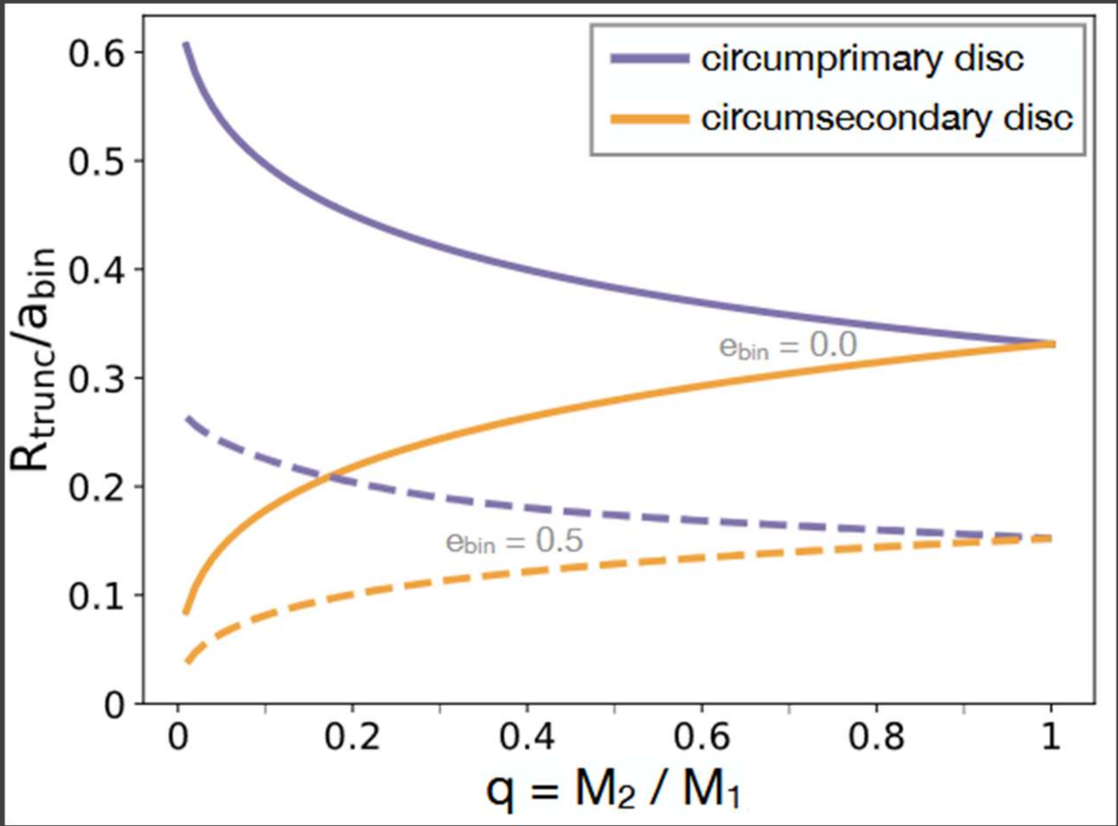
1407.8211

DF Tau binary discs

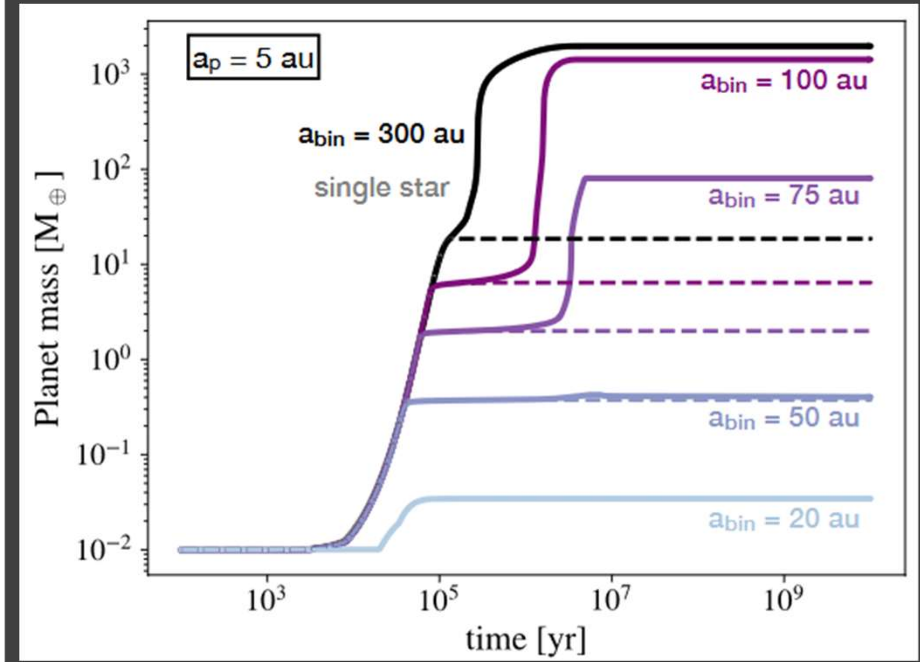


ALMA data

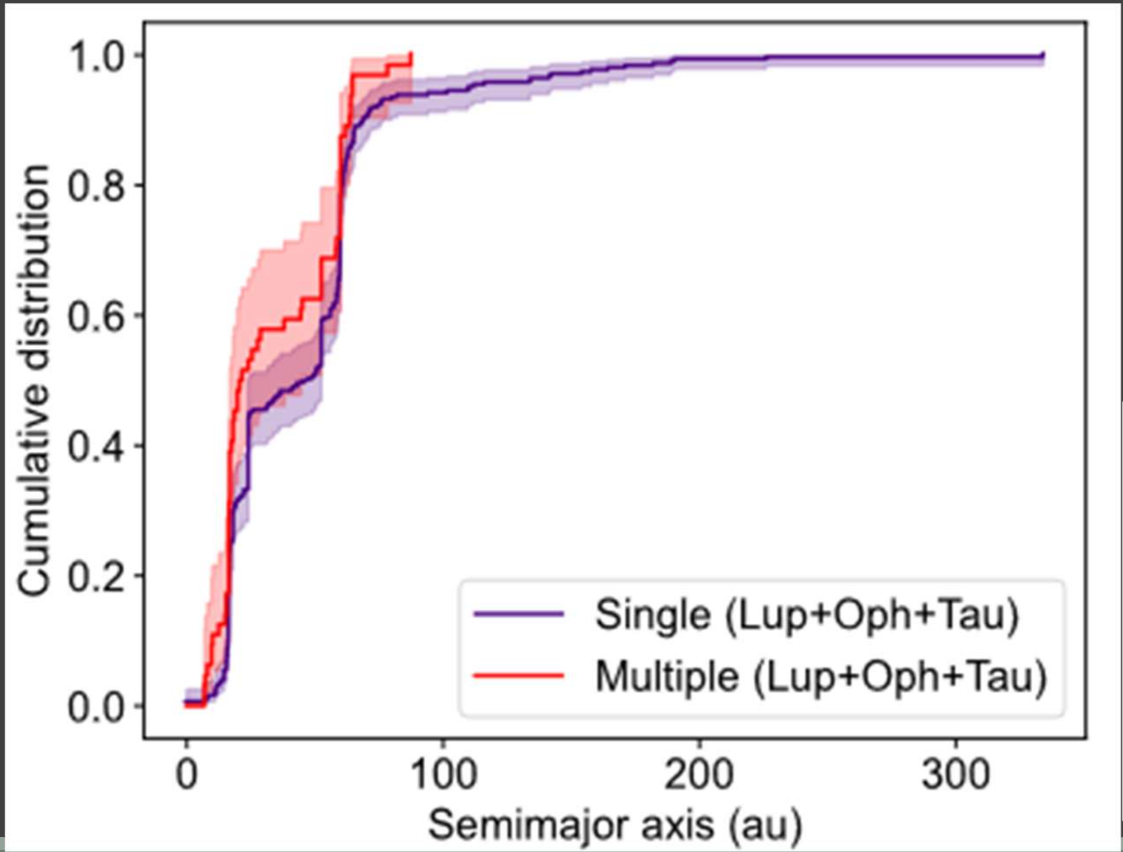
Disc truncation in binary systems

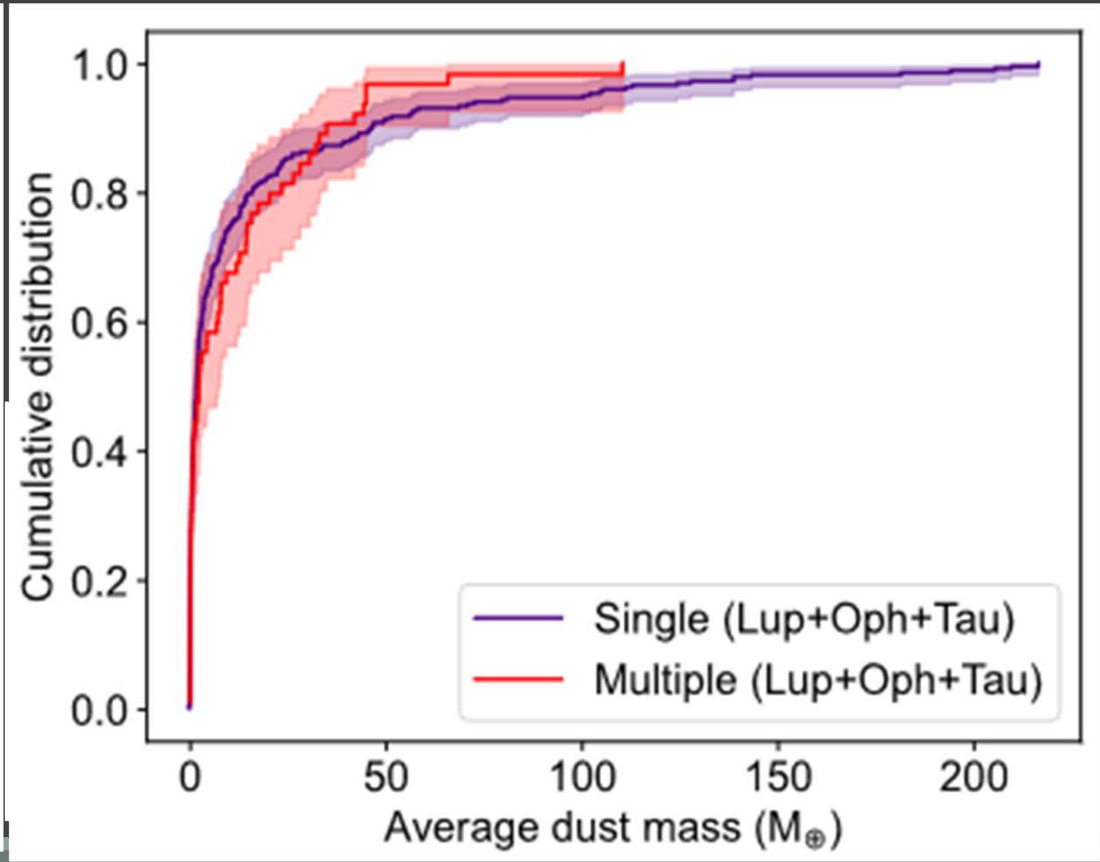


S-type binaries



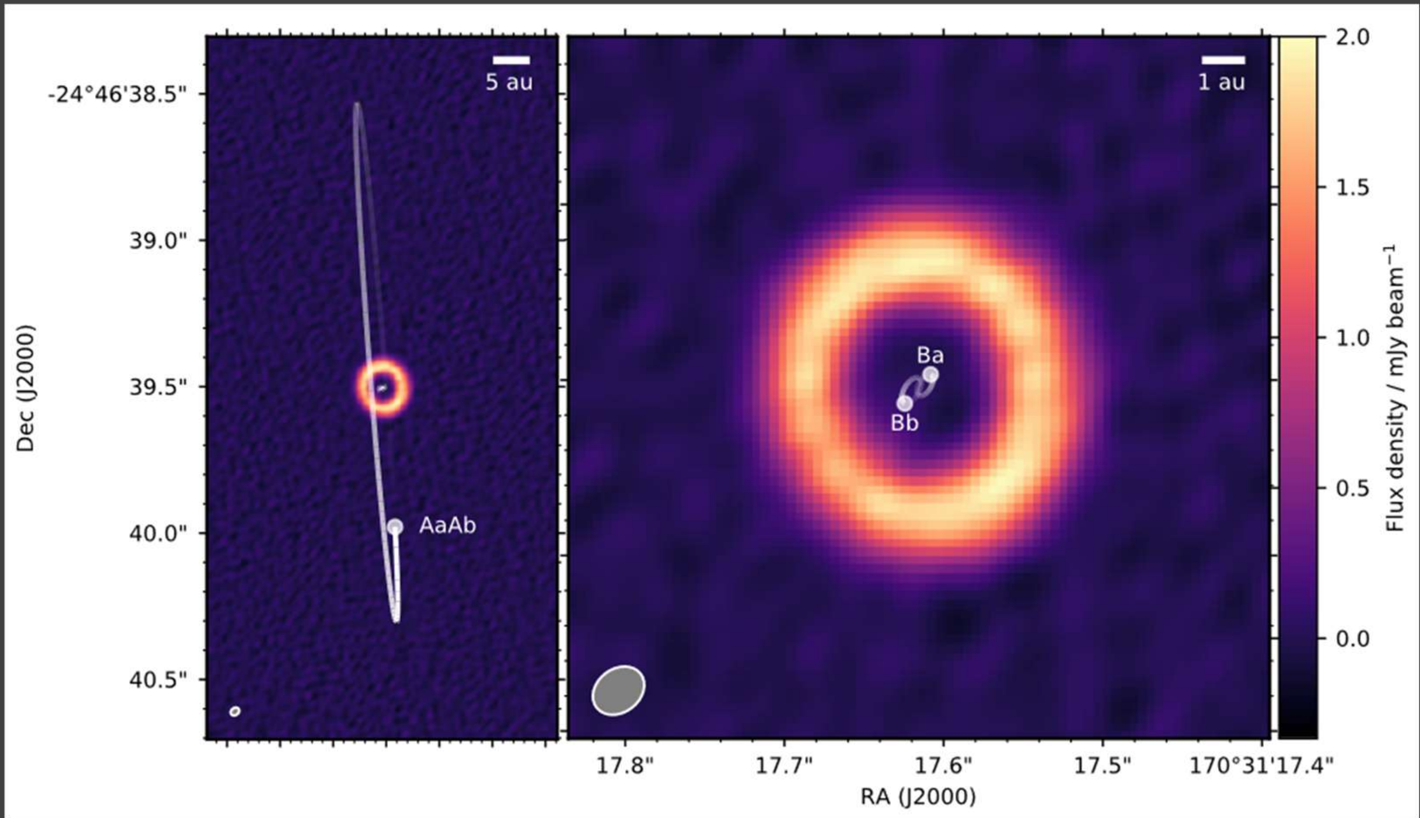
S-type discs in binaries are more compact

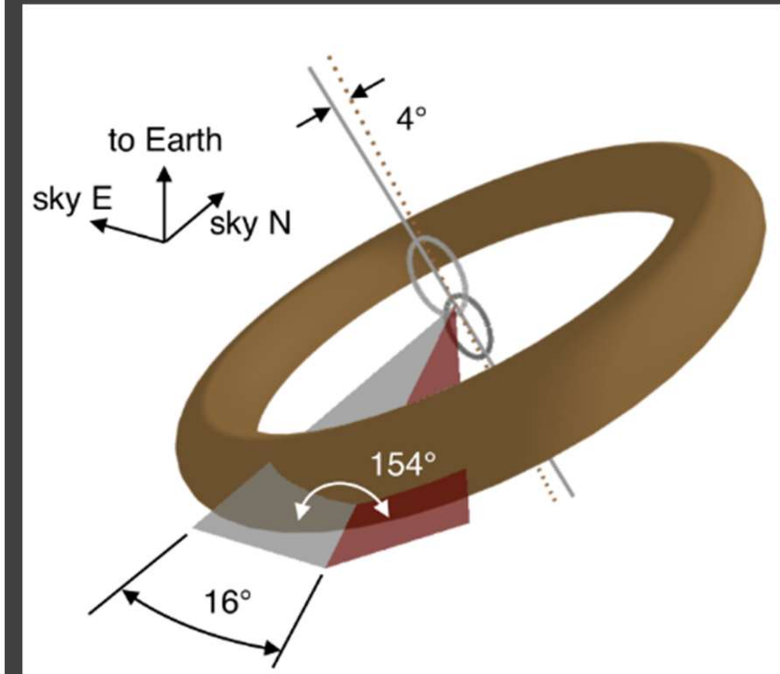




2304.14450

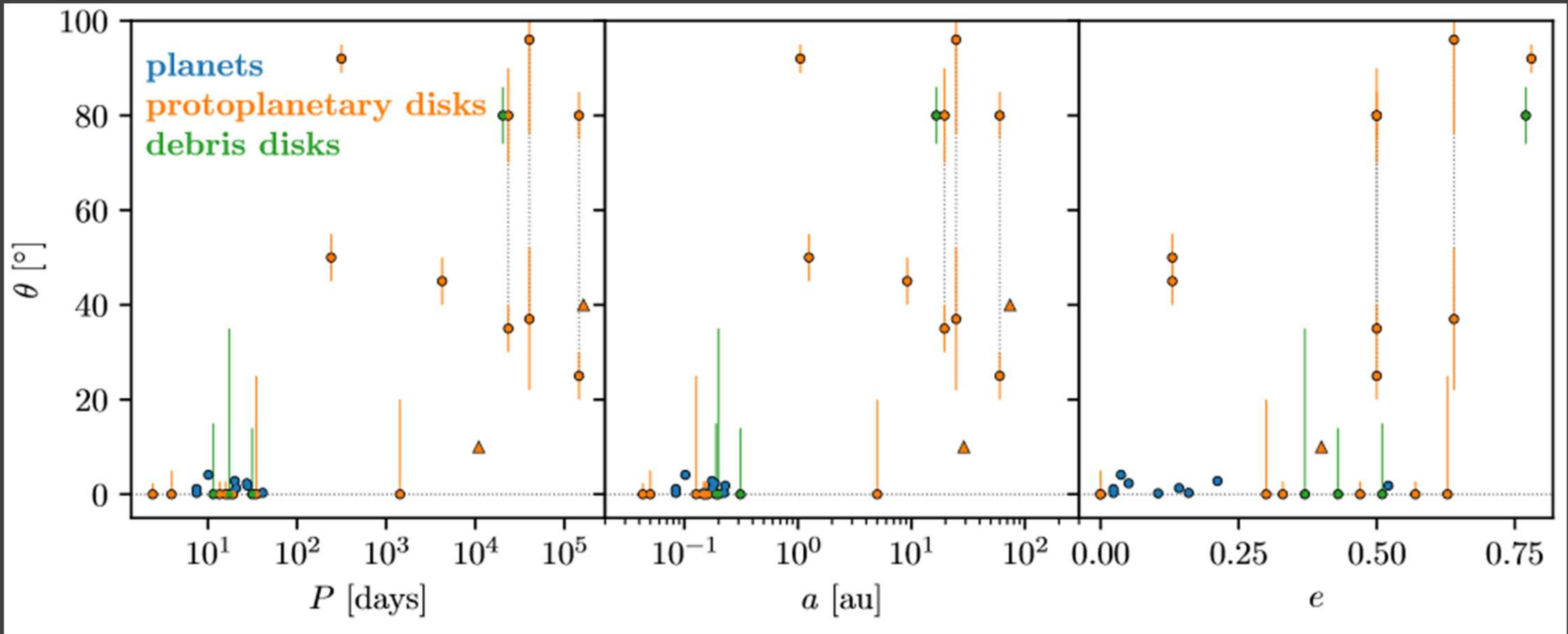
A circumbinary protoplanetary disc in a polar configuration





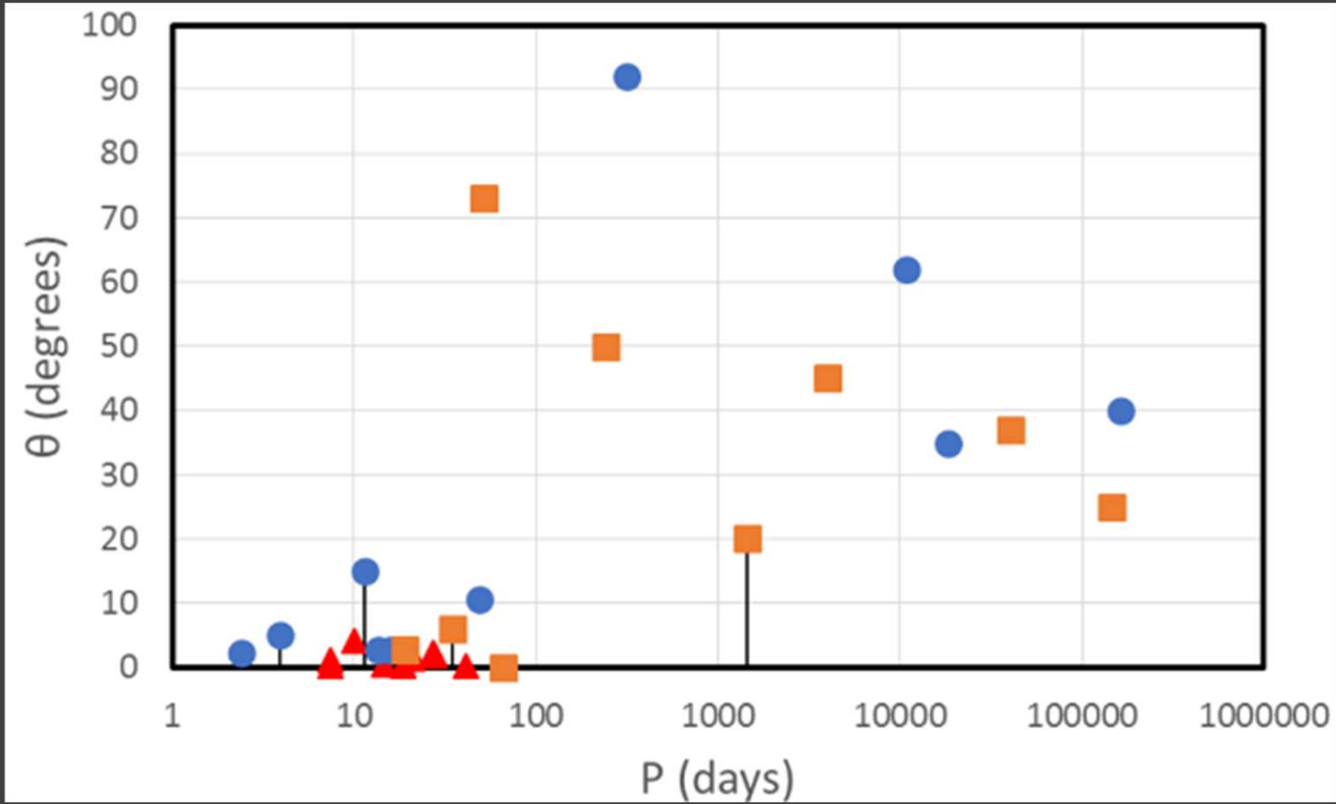
1901.05018

Circumbinary discs are often inclined



1906.03269

Discs are more inclined in wide binaries

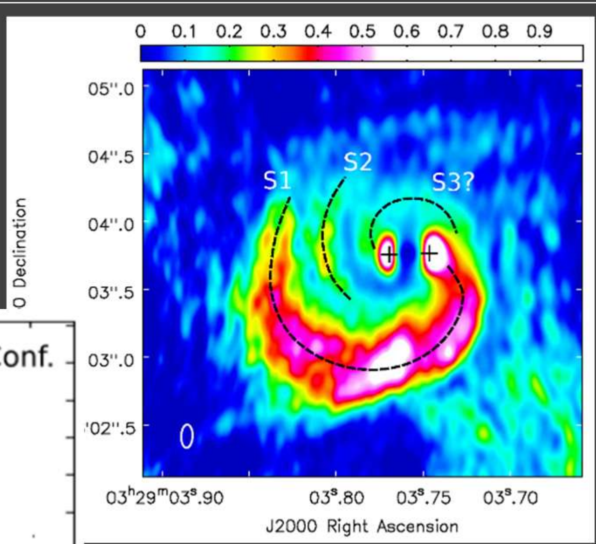


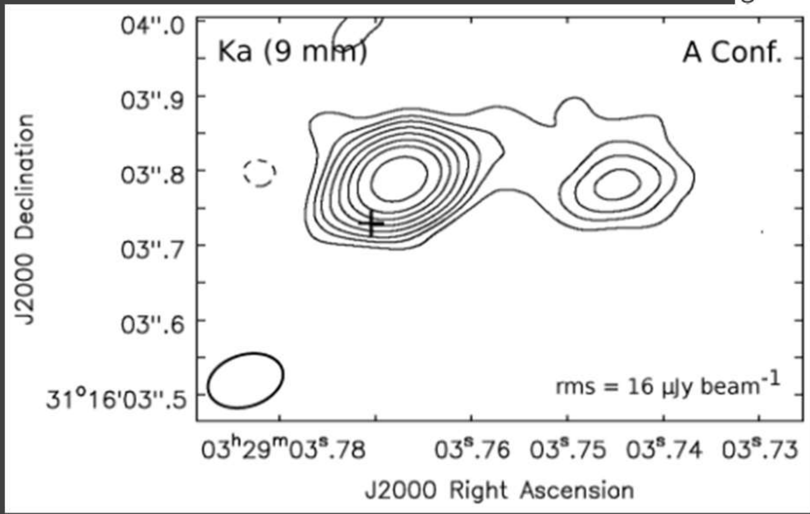
Data on S-type planets generally confirm this property.

Circumstellar and circumbinary discs

SVS 13 system

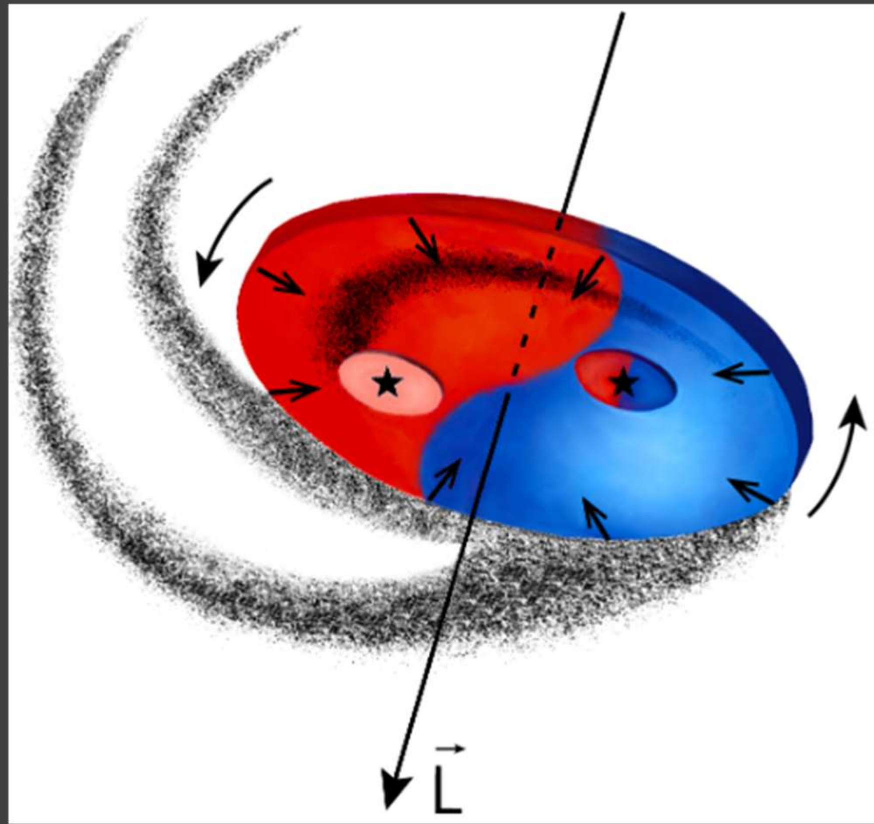
VLA and ALMA observations





ALMA

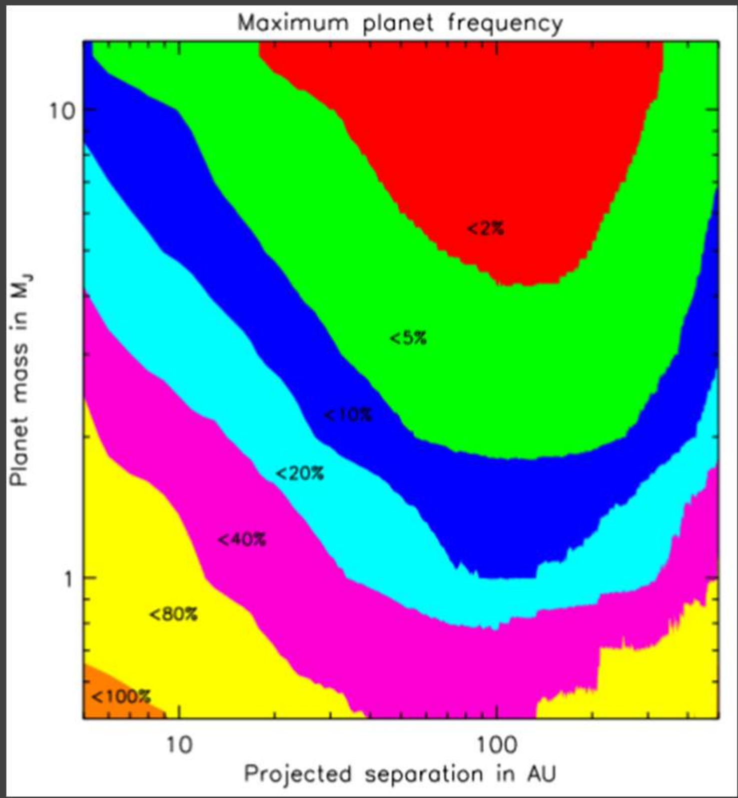
VLA



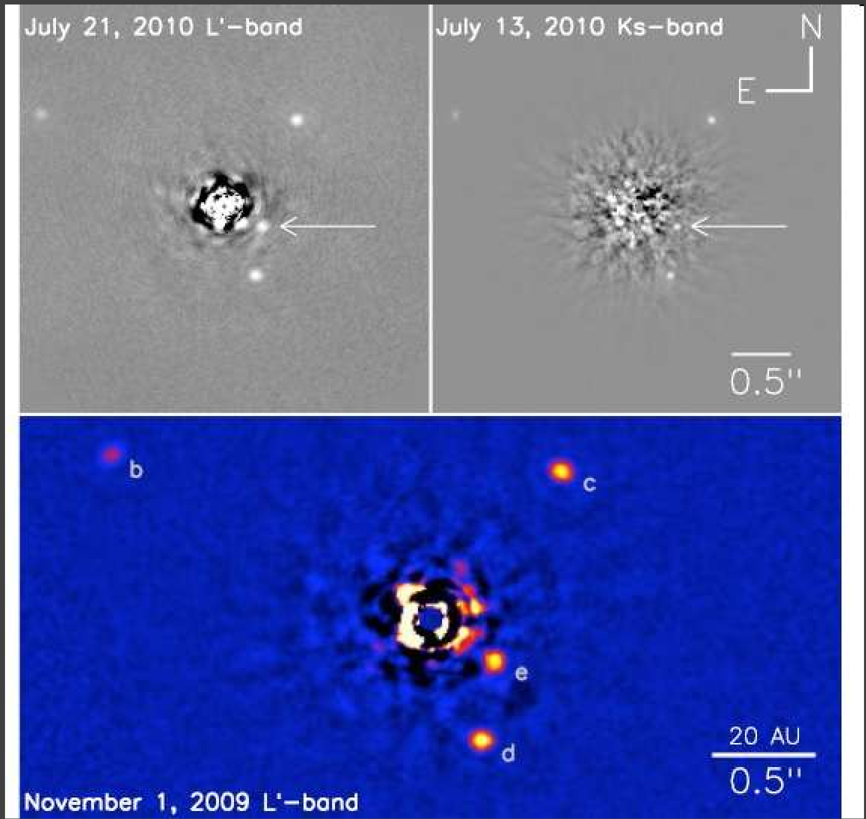
Direct imaging of planets

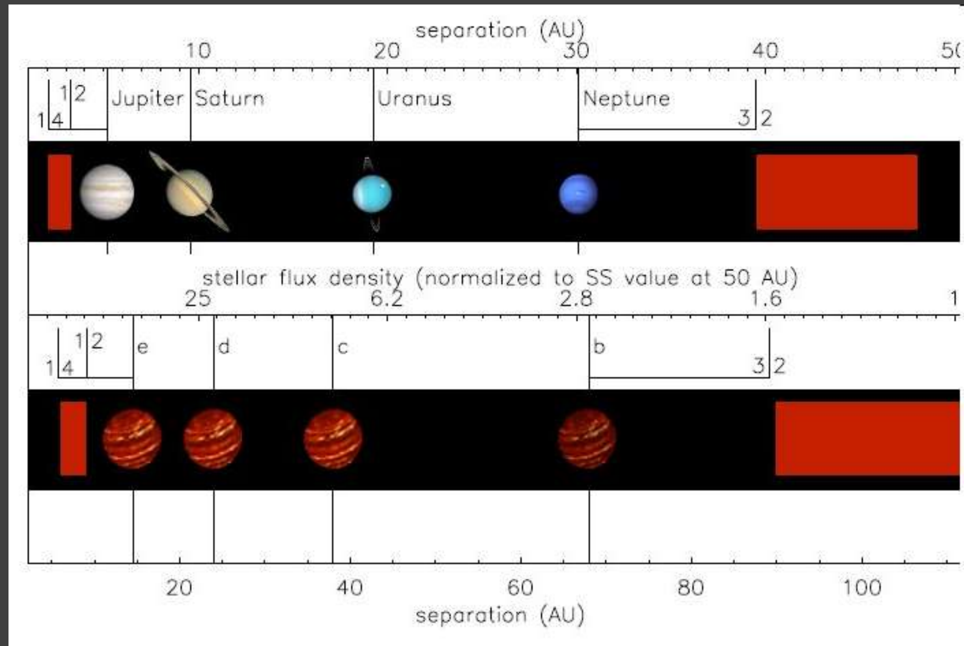
Recent survey with direct imaging resulted in an estimate that ~few percent of star have a planet 0.5-14 Mjup at 20-300 AU.

HR8799 system and several brown dwarfs were found



HR 8799

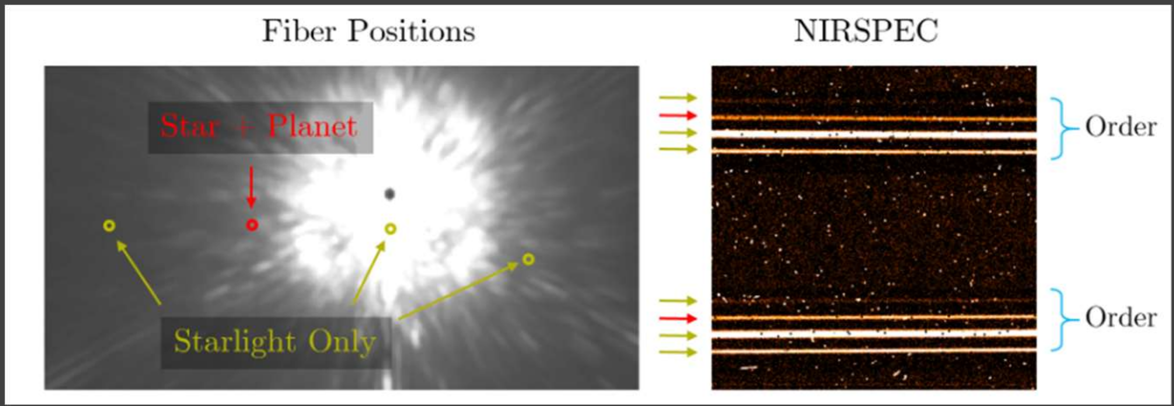


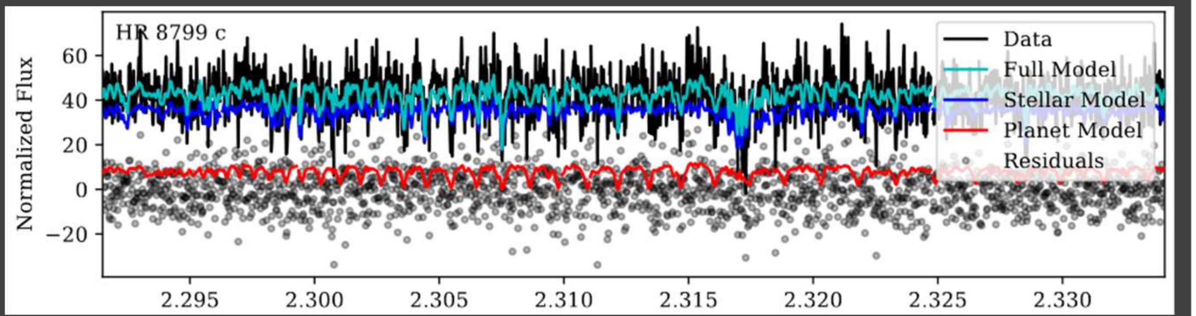


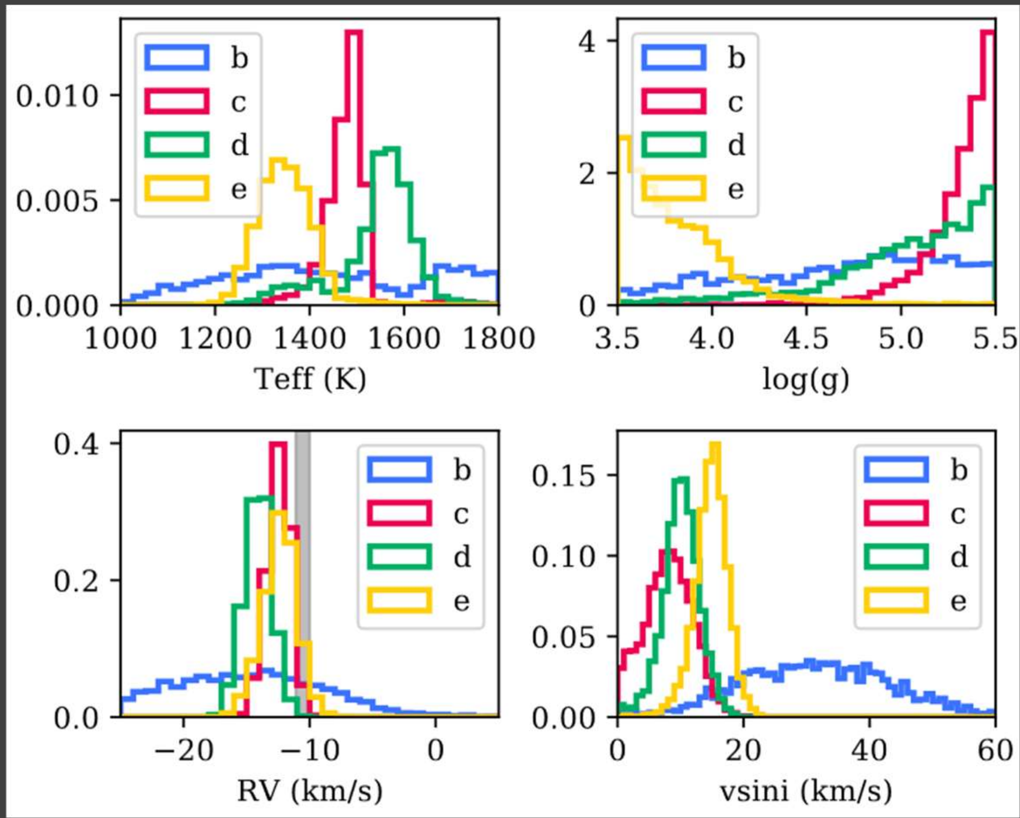
Keck II

Structure similar to the Solar system, but if expanded by factor 2

Obtaining spectra and atmospheric data

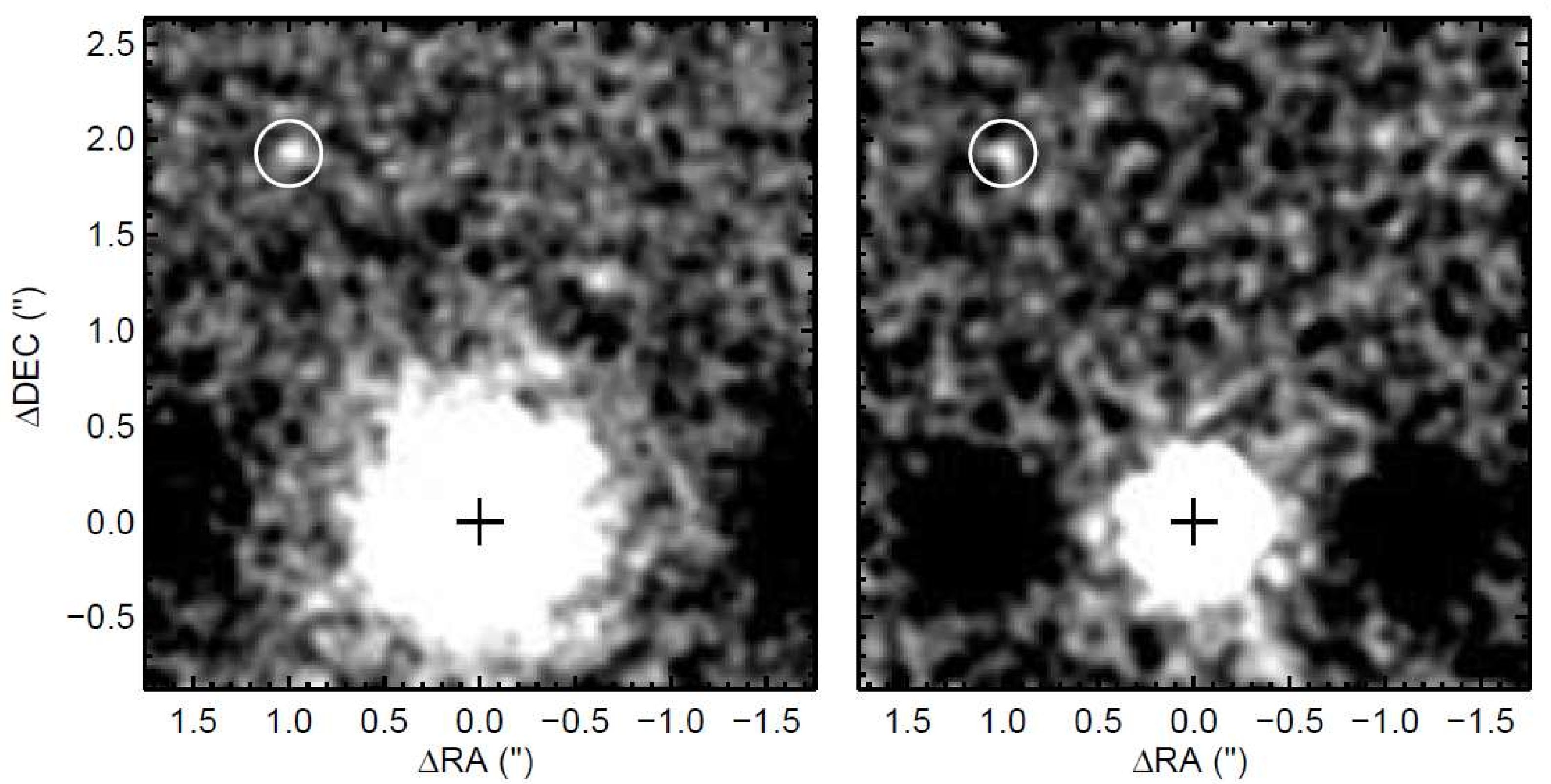






2107.06949

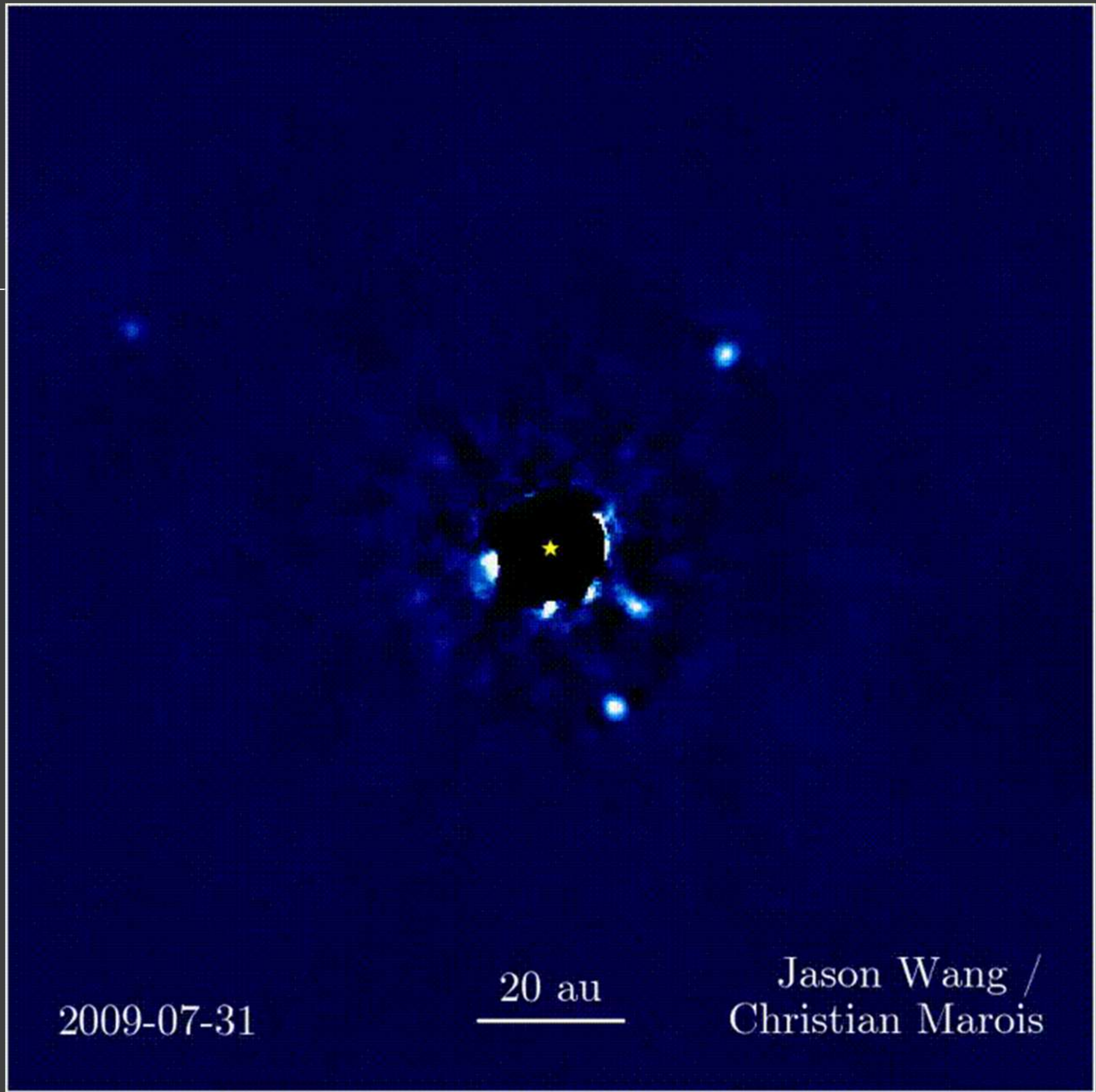
Young star 1RXS J160929.1-210524



Gemini North

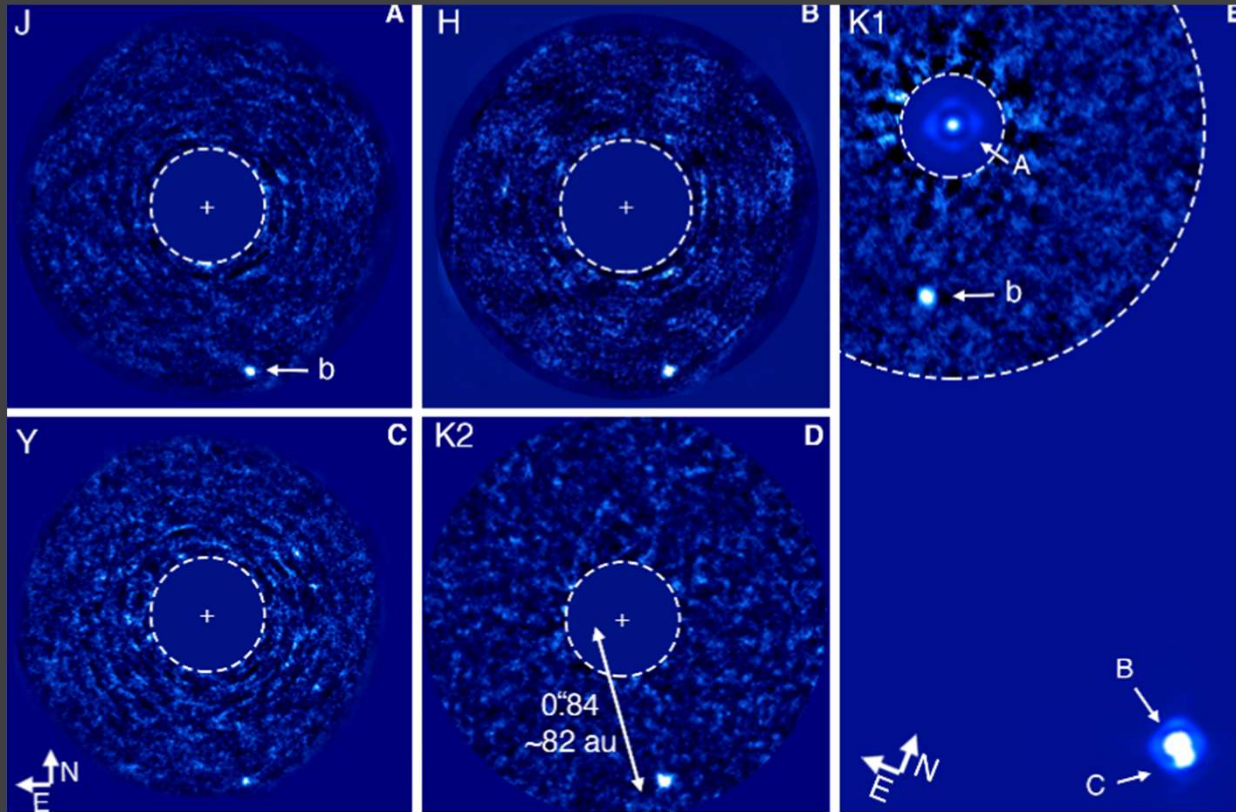
1006.3070

HR 8799



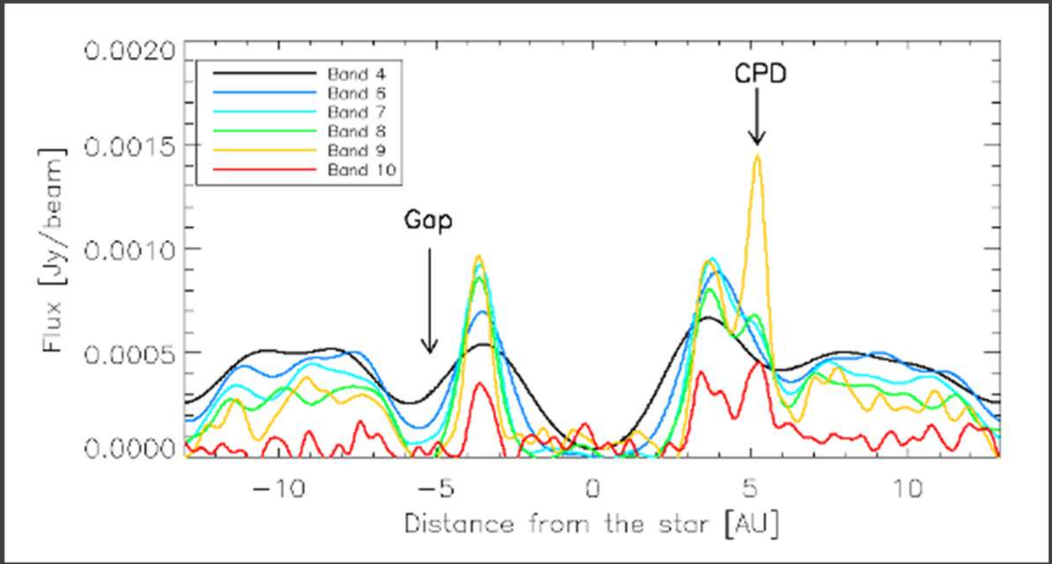
Planet in a triple system

Young planet ~16 Myr.
Observed by VLT
Orbit might be unstable.

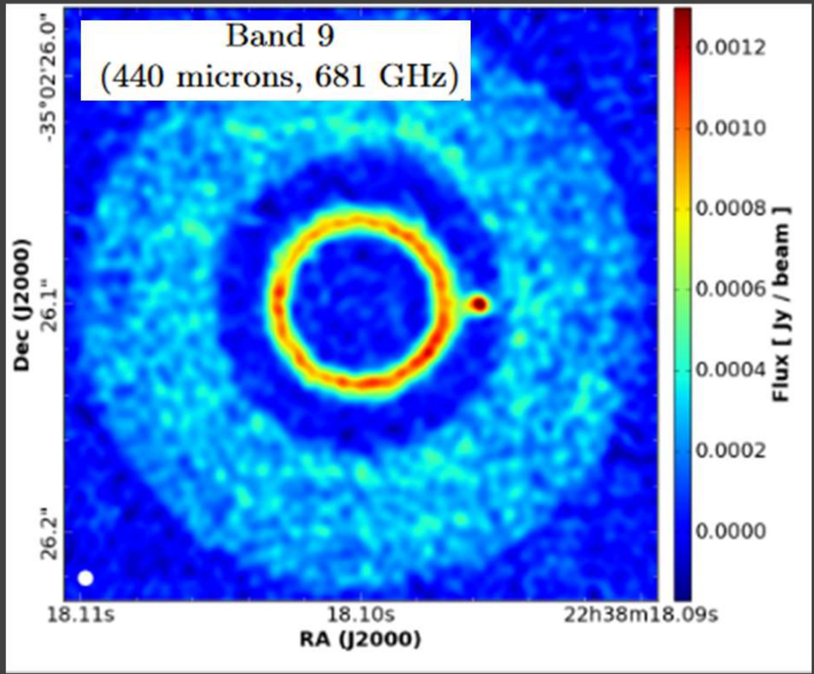


1607.02525

Circumplanetary discs (mock simulations)



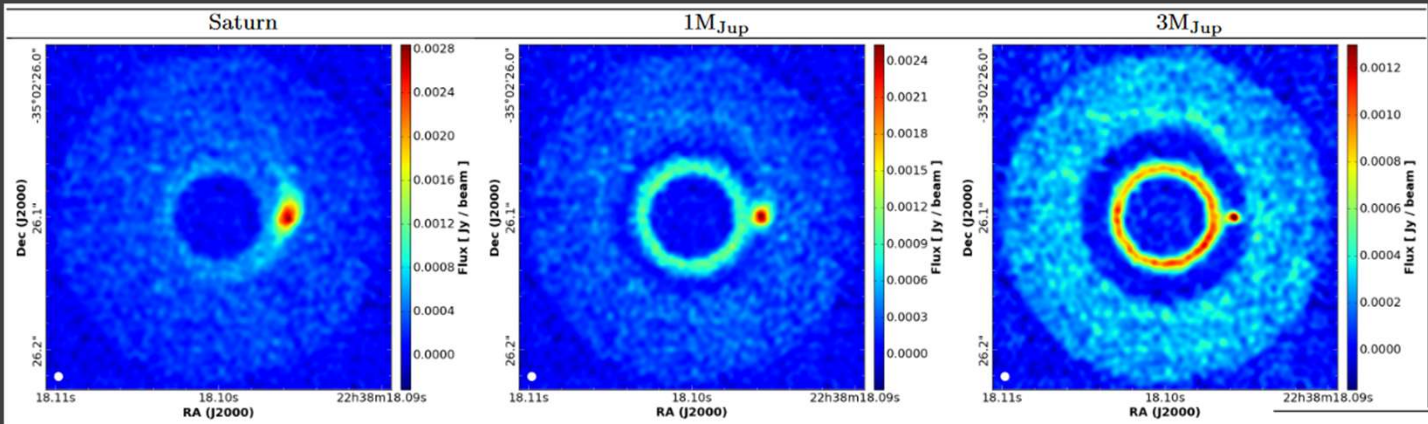
Size of a circumplanetary disc is about ½ of the Hill sphere.
Thus, it can be hardly resolved by ALMA, but can be detected.
Presently, only upper limits are available (2003.08658).

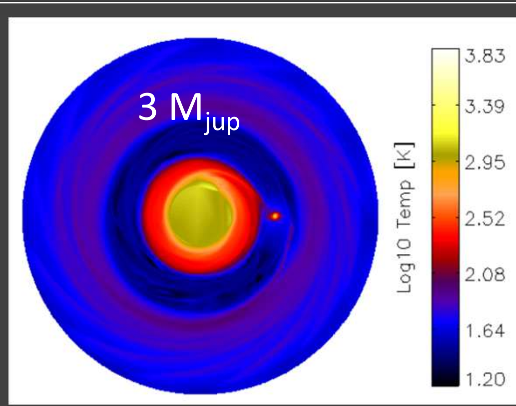


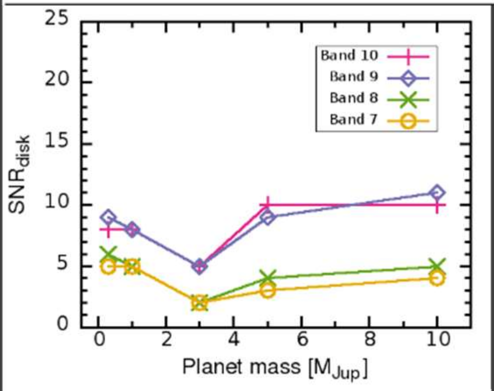
3 Jupiter masses
5 hours of observations
Better visible at shorter wavelengths
Gap opening is important
Planet temperature 4000K (age ~1 Myr)

1709.04438

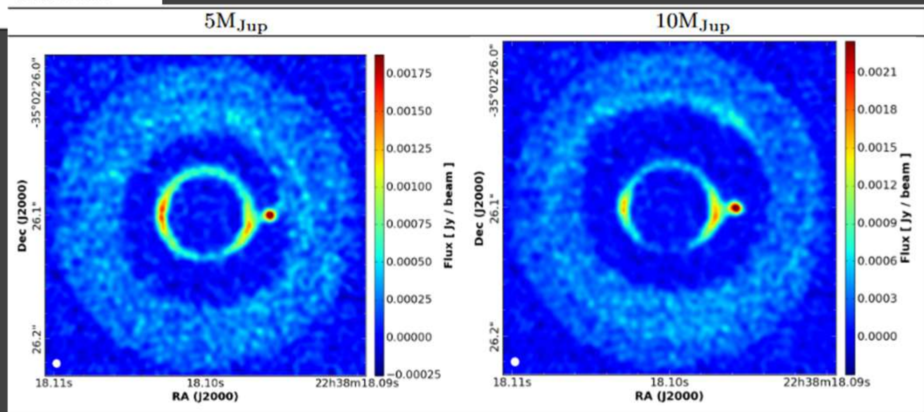
Dependence on the planet mass





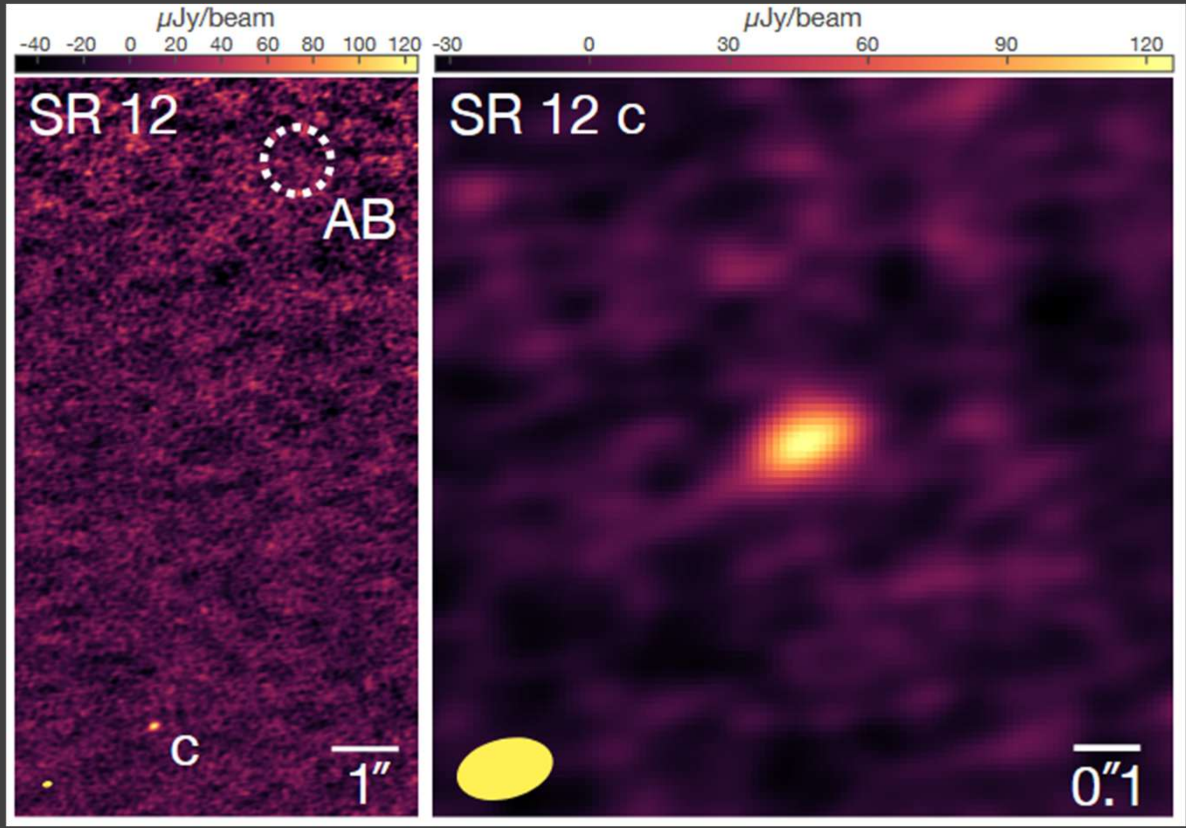


Light planets, like Saturn,
can also be detected.



Disc around a planet

ALMA observations.
Planet SR 12 c – 11 Mjup
a~980 AU
SR 12 AB – T Tau binary

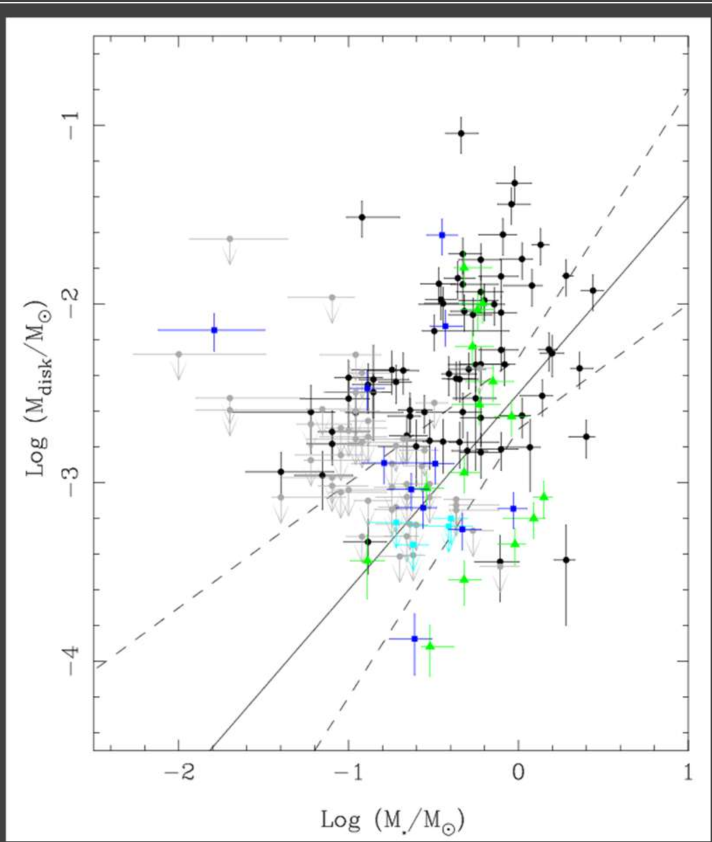


Literature

- arxiv:1703.08560 Circumstellar discs: What will be next?
- arXiv:2110.04319, 2403.11804 Debris discs
- arxiv:1602.06523 Resolved observations of transition disks
- arxiv:1607.08239 The International Deep Planet Survey II:
  The frequency of directly imaged giant exoplanets with stellar mass
- arXiv:1801.07721 Population synthesis of protostellar discs
- arXiv:2001.05007 Observations of Protoplanetary Disk Structures
- arXiv: 2009.04345 Visualising the Kinematics of Planet Formation
- arXiv: 2203.09528 Kinematic structures in disks
- arXiv: 2304.14450 Discs in binaries
- arXiv: 2410.00374 Planet-disk interaction

Statistics of circumstellar discs in binaries

17 binary systems
100-1400 AU
ALMA observations

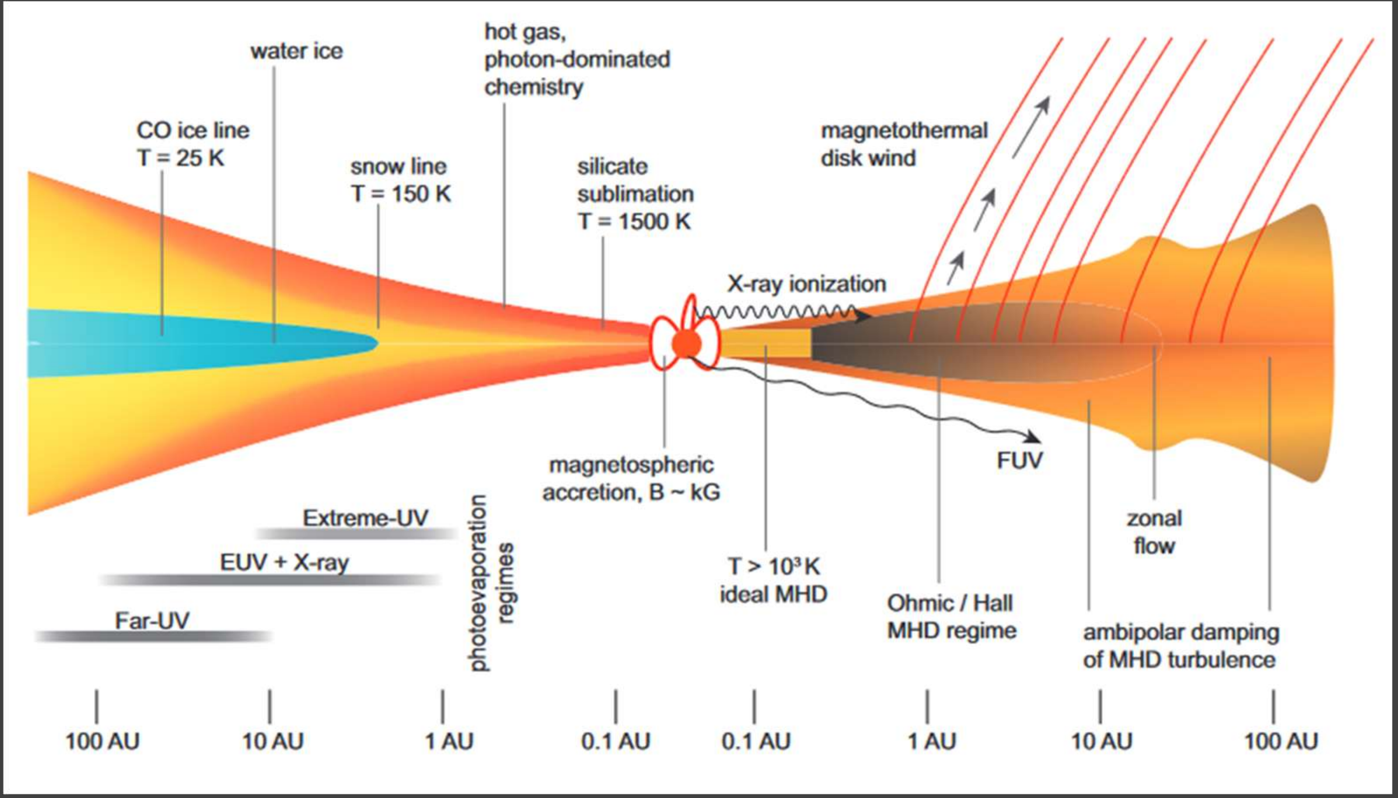


Green triangles – primaries;
Squares – secondaries
(dark blue – detected,
light blue – non-detected);
black dots – single stars
from other studies of the Tauris;
grey dods – single non-detections.

Secondary discs in two cases are brighter than discs around primaries.

1402.5363, see more recent results in 1901.05029

Disc structure



1803.10526, see also 2410.23235